A Cross-Layer Approach for Cooperative MIMO Multi-hop Wireless Sensor Networks

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Abstract—In this work, we study the problem of determining the minimum scheduling length that can satisfy end-to-end (ETE) traffic demand in scheduling-based multihop WSNs with cooperative multiple-input multiple-output (MIMO) transmission scheme. Specifically, we present a cross-layer formulation for the joint routing, scheduling and stream control problem by incorporating various power and rate adaptation schemes, and taking into account an antenna beam pattern model and the signal-to-interference-and-noise (SINR) constraint at the receiver. In the context, we also propose column generation (CG) solutions to get rid of the complexity requiring the enumeration of all possible sets of scheduling links.

Keywords—Wireless Sensor Networks, Cross-Layer Design, Cooperative MIMO System, Column Generation.

I. Introduction

In WSNs, applications such as target tracking and fire detection usually have their particular requirements on end-to-end (ETE) QoS. To meet the requirements, cross-layer optimization schemes are recently proposed to take into account the problems cross physical, medium access control (MAC) and network layers. Specifically, the corresponding wireless communication schemes can now be designed to break the limits of layering principle and to jointly solve the routing, scheduling and stream control problems with the aim of maximizing the network performance.

On the ground of cross-layer design, a MIMO antenna system in the physical layer has the potential to offer multiple Degrees of Freedom (DOFs) for communications in a node while reducing interference and improving network throughput, which attracts much attention of recent research on communication [1], [2], [3]. However, the fact that MIMO could require complex transceiver circuitry and signal processing leading to large power consumption has been shown to preclude its application to energy-constrained WSNs. To overcome this difficulty, cooperative MIMO [4] and virtual antenna array [5] are proposed to achieve the MIMO capacity in a network involving only single antenna (Single-Input Single-Output, SISO) nodes.

For such cooperative MIMO or virtual MIMO (VMIMO) networks, collaborative beamforming (CB) [6] and cooperative transmission (CT) [7] have been proposed as new communication schemes to fully utilize spatial diversity and multiuser diversity. The idea behind them is to allow wireless nodes to transmit or relay information for each other so that these collaborative or cooperative nodes can create a virtual MIMO network. In this work, it is considered that CB has the promise of greatly improving network performance by increasing the transmit power gain due to less transmit power being scattered in unintended directions. With the MIMO system and CB transmission (MIMO-CB), the objective of this work is thus to compute the minimum scheduling length that can satisfy the ETE traffic demand for a set of source-destination pairs with different power and rate adaptation schemes. Specifically, for a given network configuration and its traffic demand, we formulate the minimum scheduling length problem (MSLP) as a linear programming (LP) and its column generation (CG) subprogram as a integer programming (IP) or mixed linear integer programming (MLIP) problem. In what follows, we introduce the system model, give our formulation, and examine its performance by simulation experiments.

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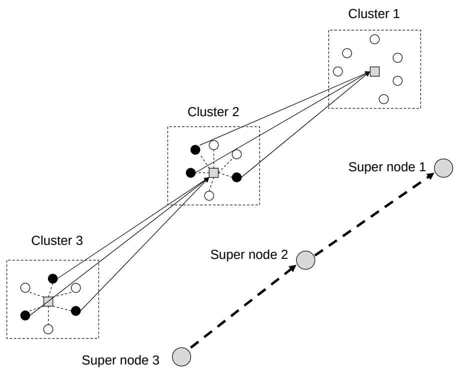


Fig. 1. Multi-hop virtual MIMO with collaborative beamforming.

II. Problem Formulation

A. Communication Model of Collaborative Beamforming

As shown in Fig. 1, the WSN under consideration is composed by N randomly located nodes in (x, y) plane, and organized into k_c clusters. Each of the nodes has a single antenna and operates in a half duplex mode. The rectangular coordinates of a node, (x_k, y_k), $k = 1, ..., N$, is conveniently represented by the polar ones of $\left(r_k = \sqrt{(x_k^2 + y_k^2)}, \psi_k = tan^{-1}\left(\frac{y_k}{x_k}\right)\right)$. Let M_i, $i \in \{1, 2, ..., k_c\}$ be a cluster of nodes located within the coverage range and $C_i \subset M_i$ be a set of collaborative nodes to be selected from M_i.

To transmit, the source cluster head (CH), say CH_i, first broadcasts its data to the cluster members M_i. Then, the $n_i = |C_i|$ cooperative nodes (CN) selected from M_i will transmit the data to the next cluster head (CH), say CH_j,

$j \in \{1, 2, ..., k_c\} \backslash i$ if scheduled. Assume that the transmission target, say CH_1, is located at the direction of φ_1. In order to construct a main lobe towards CH_1, the carrier of each should be synchronized with initial phase $\Psi_k = -\frac{2\pi}{\lambda} d_k(\varphi_1)$, where λ denotes the wavelength and $d_k(\phi) \approx A - r_k \cos(\phi - \psi_k)$ is the Euclidean distance between the k^{th} node and a point (A, ϕ) at the refernce sphere $r = A$. With that, for the n_i nodes, the far-field beampattern can be given by

$$F(\phi/C_i) = \frac{1}{n_i} \sum_{k \in C_i} e^{j \frac{2\pi}{\lambda} r_k [\cos(\varphi_1 - \psi_k) - \cos(\phi - \psi_k)]} \quad (1)$$

Then, the antenna gain can be represented by [6]

$$G(\phi/C_i) = \frac{2\pi F(\phi/C_i)}{\int_0^{2\pi} F(\phi/C_i) d\theta} \quad (2)$$

B. Network and Communication Model

The multi-hop WSN in the context is represented by the graph of $G = (V, E)$, where V denotes a set of **super nodes**, in which a super node i, or simply node i, represents a cluster i (as shown in Fig. 1), and E denotes a set of links, in which a link $\{i, j\}$ represents a node i using the beamforming or multiple-input single-output (MISO) transmission to communicate with node j, or more precisely CH_j. For each link in E, the receive power is considered by [8]

$$P_{r_{\{i,j\}}} = \frac{P_{t_{\{i,j\}}} G_{t_{\{i,j\}}} G_{r_{\{i,j\}}}}{\gamma^{\alpha}_{\{i,j\}}} \left(\frac{\lambda}{4\pi}\right) \quad (3)$$

where $P_{t_{\{i,j\}}}$ denotes the transmit power of node i, $G_{t_{\{i,j\}}}$ the corresponding transmit power gain, $G_{r_{\{i,j\}}}$ the receive power gain, $\gamma_{\{i,j\}}$ the Euclidean distance between i and j, and α the pathloss factor. Note that the gain $G_{t_{\{i,j\}}}$ obtained from (2) is proportional to n_i^2 rather than n_i. On the other hand, $G_{r_{\{i,j\}}}$ equals one here because each node including CH_j has the same isotropic antenna. Given P_r's and η_j that is the thermal noise at receiver CH_j, the SINR at receiver CH_j due to transmission from i in the presence of other transmissions will be

$$SINR_{\{i,j\}} = \frac{P_{r_{\{i,j\}}}}{\eta_j + \sum_{k \neq i,j} P_{r_{\{k,j\}}}} \quad (4)$$

With W denoting its bandwidth, the capacity of this link can then be obtained by the Shannon theory as [9]

$$LC_{\{i,j\}} = W \log_2(1 + SINR_{\{i,j\}}) \quad (5)$$

C. Scheduling with Spatial-TDMA

In this work, we adopt Spatial-TDMA (STDMA) [10] as the MAC layer to guarantee the ETE QoS, and seamlessly integrate the SINR constraint into the scheduling. To this end, we let $T_M \subset E$ be a set of links that can be concurrently activated if all the receivers of these links in T_M have their SINR values higher than ζ. If T_M can satisfy this constraint, it is called a *transmission mode*. We then define a scheduling matrix as an indexed collection, $\Gamma = \{T_M^1, T_M^2, ..., T_M^s\}$, where the index s could be an arbitrarily large finite number. A schedule S is feasible if there exists a scheduling vector, $\mathbf{p} = [p_{tm}^1, ..., p_{tm}^s]$ with its length, called *scheduling length*, satisfying $\sum_{k=1}^{s} p_{tm}^k \leq 1$, where $p_{tm}^k \leq 0$, $1 \leq k \leq s$ denotes the duration that all the links in T_M^k can be simultaneously active in the periodically recurring time frames of STDMA.

D. The minimum scheduling length problem (MSLP)

Now, given the source-destination pairs of M end-to-end communication sessions, $\{s_m, d_m\}$, $1 \leq m \leq M$, our aim is thus to find the minimum scheduling length that can fulfill the ETE QoS requirement of WSN operated under VMIMO-CB. To this end, we consider 1) a rate allocation $\mathbf{r}$ specifying the rate r_m for each session m, as the stream control variable, 2) a flow allocation vector $\mathbf{f^m}$ specifying the amount of traffic $f^m_{\{i,j\}}$ of session m routed through link $\{i, j\}$, as the routing variable, and 3) a transmission scheduling vector $\mathbf{p}$ specifying time fraction $p^k_{t_m}$ for each transmission mode T_M^k, as the scheduling variable. With the above, the minimum scheduling length problem **[MSLP]** is to minimize

$$\tau = \sum_{k=1}^{s} p_{tm}^k \quad (6)$$

subject to:

$$\sum_{\{i,j\} \in E_{s_m}^{out}} f^m_{\{i,j\}} - \sum_{\{i,j\} \in E_{s_m}^{in}} f^m_{\{i,j\}} = r_k, 1 \leq m \leq M \quad (7)$$

$$\sum_{\{i,j\} \in E_v^{out}} f^m_{\{i,j\}} - \sum_{\{i,j\} \in E_v^{in}} f^m_{\{i,j\}} = 0,$$
$$1 \leq m \leq M, \ \forall v \in V \backslash \{s_m, d_m\} \quad (8)$$

$$\sum_{m=1}^{M} f^m_{\{i,j\}} \leq \sum_{\forall T_M^k \in \Gamma : \{i,j\} \in T_M^k} p^k_{t_m} \cdot LC_{\{i,j\}}, \forall \{i, j\} \quad (9)$$

$$\sum_{k=1}^{s} p^k_{t_m} = 1 \quad (10)$$

$$f^m_{\{i,j\}} \geq 0, \quad 1 \leq m \leq M, \forall \{i, j\} \quad (11)$$

$$p^k_{t_m} \geq 0, \quad 1 \leq k \leq s \quad (12)$$

$$r_m \geq TL_m, \ 1 \leq m \leq M \quad (13)$$

In the set of constraints, (7) represents the conservation law for source nodes to ensure that the net amount of traffic going out of the source node of a session is equal to that of the end-to-end session rate, where $E_{s_m}^{out}$ ($E_{s_m}^{in}$) denotes the set of outgoing (incoming) edges of source node s_m. (8) represents the conservation law for intermediate nodes to ensure that the amount of traffic of a session entering any intermediate node is equal to that existing the intermediate node, where E_v^{out} (E_v^{in}) denotes the set of outgoing (incoming) edges of node $v \in V \backslash \{s_m, d_m\}$. (9) gives the bandwidth constraint to make sure that the total traffic on a link is no more than the average link transmission rate. (10) gives the scheduling constraint, forcing that the summation of all elements in a transmission schedule vector is equal to 1. (11) and (12) simply represent the valid constraints for flow rate and scheduling vector, respectively, and (13) gives the traffic load demand TL_m for each session m. Finally, we note that without limits on the $f^m_{\{i,j\}}$'s involved, a session m can be routed through different links, $\{i, j\}$'s, towards its destination, which is usually called traffic splittable.

III. Minimum Scheduling Length Computation

As can be seen in above, MSLP is in general a linear programming problem and there may exist $s = 2^{|E|}$ such modes to be enumerated, which is not computationally efficient. For the time complexity, we adopt a *column generation* (CG) approach to decompose the original problem into a *master problem* and a *sub-problem*. The strategy of the CG decomposition is to operate iteratively on two separate, easier-to-solve problems [11]. The master problem will pass down a new set of cost coefficients to the sub-problem, and then receives a new column (i.e., a new transmission mode in this case) based on these cost coefficients from the sub-problem.

When considering sub-matrix $\Gamma^o \subset \Gamma$ with its index $s^o \leq s$, we can formulate the master problem as follows:

$$\textbf{[Master]}: \min \left(\sum_{k=1}^{s^o} P_{tm}^k \right) \tag{14}$$

subject to the same set of constraints given in (7)- (13).

A. Sub-problem

When the master problem is solved, the column generation approach requires to identify whether the result can be re-optimized by adding a new column or transmission mode to Γ^o. Let $w_{\{i,j\}}$ be the dual variables obtained from the **Master** problem. The reduced cost C_{T_M} for a column (transmission mode) T_M will be

$$C_{T_M} = 1 - \sum_{\{i,j\} \in T_M} w_{\{i,j\}} T_{M_{\{i,j\}}} \tag{15}$$

Specifically, to find a new column giving the most negative reduced cost, we need to solve a subproblem with the following objective:

$$\min_{\forall T_M} C_{T_M} = 1 - \max_{\forall T_M} \sum_{\{i,j\} \in T_M} w_{\{i,j\}} T_{M_{\{i,j\}}} \tag{16}$$

Apparently, the above sub-problem depends on the power/rate adaptation schemes to be employed and the restrictions on the VMIMO-CB transmission. Hence, in the following we consider the different sub-problem formulations that could be resulted for the energy-efficient cross layer optimization.

1) Fixed Transmit Power (FP): With this scheme, each node uses its maximum transmit power (P_{max}) for its transmission, if its link $\{i,j\} \in T_M^k, 1 \leq k \leq s$, has the SINR value exceeding the minimum requirement ζ. Thus, associating the predefined ζ with a transmission rate in (5) implies a fixed rate transmission scheme for a fixed P_{max}. To formulate the sub-problem for this scheme, we introduce Boolean variables with value $x_{\{i,j\}} = 1$ to denote an active link $\{i,j\}$, and with 0 to denote the otherwise. Given that and dual variable $w_{\{i,j\}}$, the sub-problem can be formulated as follows.

$$\textbf{[Sub-FP]}: \max \left(\sum_{\{i,j\} \in E} w_{\{i,j\}} x_{\{i,j\}} \right) \tag{17}$$

subject to

$$\left(\eta_j + \sum_{a \neq i,j} P_{r_{\{a,j\}}}^{max} - \zeta^{-1} P_{r_{\{i,j\}}}^{\max} \right) x_{\{i,j\}} + \sum_{a,b \neq i,j} P_{r_{\{a,j\}}}^{max} x_{\{a,b\}} \leq \sum_{a \neq i,j} P_{r_{\{a,j\}}}^{\max}, \ \forall \{i,j\} \in E \tag{18}$$

$$\sum_{j:\{i,j\} \in E} x_{\{i,j\}} + \sum_{j:\{j,i\} \in E} x_{\{j,i\}} \leq 1, \ \forall i \in V \tag{19}$$

$$x_{\{i,j\}} \in \{0,1\}, \qquad \forall \{i,j\} \in E \tag{20}$$

where $P_{r_{\{x,y\}}}^{max}$ denotes the receive power in (3) for node y when node x uses P_{max} to transmit. In the formulation, the binary integer variables, $x_{\{i,j\}}$'s, are used to select the set of links that can be simultaneously activated. This selection obviously involves the SINR constraint in (4). Specifically, the design principle is clearly shown in (18) that if link $\{i,j\}$ is selected, its SINR value from (4) should be larger than or equal to ζ, whereas if $\{i,j\}$ is not selected, the resulted should be at least an valid constraint for the system. Apart from that, it is shown in (19) that these variables are also required to satisfy the contention constraint, enforcing that a node can not send and receive at the same time due to the half duplex nature.

2) Variable Transmit Power (VP): The above FP scheme has been considered for STDMA in [12] due to its simplicity. However, by fixing the transmit power, the system can not gain any additional link capacity even if the SINR on some links remarkably exceeds ζ, which obviously wastes the energies. In addition, the maximum power used can result in higher interference, leading to a smaller number of links to be concurrently activated. Thus, the VP scheme is proposed to alleviate these problems by allowing each source node to vary its transmit power up to the maximum P_{max} under the constraint that the SINR of all the active links should exceed a given ζ. Although the set of concurrent links resulted still has the same data rate, the source nodes can gain the performance benefit on their transmit powers lower than P_{max} to save the energies.

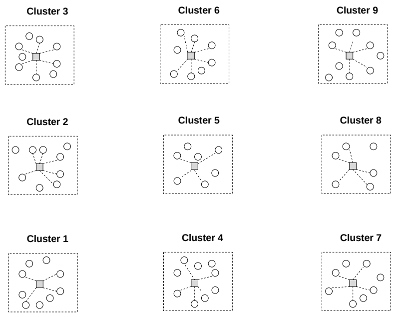
To formulate this scheme, in addition to the Boolean variable $x_{\{i,j\}}$ for each link $\{i,j\}$, we add a transmit power variable $P_i \leq P_{max}$ for each node i in the VMIMO-CB network. With these variables to consider the SINR constraint and the contention constraint in the above, we can express this sub-problem as the following mixed binary integer linear programming problem:

$$\textbf{[Sub-VP]}: \max \left(\sum_{\{i,j\} \in E} w_{\{i,j\}} x_{\{i,j\}} \right) \tag{21}$$

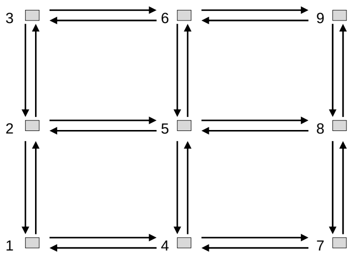
subject to

$$\zeta \left(\eta_j + \sum_{a \neq i,j} P_{r_{\{a,j\}}}^{max} \right) x_{\{i,j\}} + \zeta \sum_{a \neq i,j} P_{r_{\{a,j\}}} - P_{r_{\{i,j\}}} \leq \zeta \sum_{a \neq i,j} P_{r_{\{a,j\}}}^{max}, \qquad \forall \{i,j\} \in E \tag{22}$$

$$\sum_{j:\{i,j\} \in E} x_{\{i,j\}} + \sum_{j:\{j,i\} \in E} x_{\{j,i\}} \leq 1, \ \forall i \in V \tag{23}$$



(a)



(b)

Fig. 2. Experiment topology: (a) the node graph, and (b) the initial set of flows for the experiment.

$$x_{\{i,j\}} \in \{0,1\}, \qquad \forall\{i,j\} \in E \tag{24}$$

$$0 \leq P_i \leq P_{max}, \qquad \forall i \in V \tag{25}$$

IV. Experiment Results

In this section, we report on numerical results for the cross-layer schemes given previously. As abstractly represented in Fig. 2(a), the network of $N = 1200$ sensor nodes being divided into $k_c = 9$ clusters and each of them having $M_i \approx 133$ nodes randomly distributed over an area of $2u \times 2u$ is conducted as our simulation environment, where u denotes the wavelength of carrier under consideration.[1] In which, each cluster i selects $n_i = 100$ for communication and selects the node closest to the centre as its head CH_i. In addition, if each $CH_i, \forall i$ is exactly located at its cluster centre, the horizontal (vertical) distance between two neighboring CHs will be $200u$. In fact, with the random deployment, the location of a CH_i is not exactly the centre of cluster i in usual, and thus the distance of $200u$ is only an average value. For the different power/rate adaptation schemes, we consider $P_t = P_{max} = 1$ for PF while $0 < P_t \leq P_{max}(= 1)$ for VP. However, there are the same parameters of $W = 250$ KHz, $\alpha = 3$, $\zeta = 8$, and $\eta = 10^{-10}$ for both schemes.

Without loss of generality, we consider the initial Γ^o shown in Fig. 2(b) with $s^o = 24$. Note that $P_{t_{\{i,j\}}}, \forall\{i,j\} \in \Gamma^o$ for VP is randomly chosen with a value of $(0,1)$ to satisfy the SINR requirement of ζ. Given the above, we conduct two sessions, $\{s_1 = 1, d_1 = 9\}$ and $\{s_2 = 9, d_2 = 1\}$, with their traffic loads $TL_1 = 33$ Kbps and $TL_2 = 66$ Kbps, respectively, as the targets of transport layer to be achieved in the MSLP problem. Finally, 100 iterations of the CG approach are performed for each of the power/rate adaptation schemes to clearly exhibit their performance differences.

[1]As an example with a specific u and the related parameters, a simulated beam pattern is conduced in [13] by randomly distributing 100 nodes over an area of circle with diameter equal to $2u = 60$ cm, for the carrier frequency of 1 GHz.

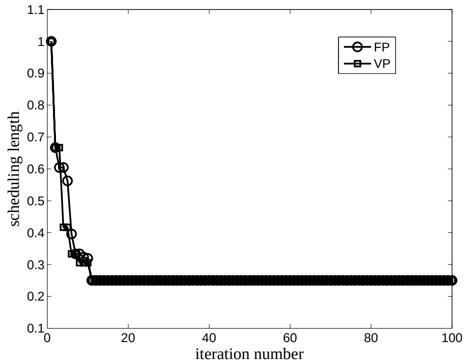


Fig. 3. Performance comparison: fixed transmit power vs. variable transmit power.

The results are shown in Fig.3. Clearly, it exhibit that around the 10th iteration both schemes of FP and VP converge to the minimum scheduling length of 0.25, and such rapid convergence well confirms the CG approach's efficiency. We note that the minimum length of 0.25 is expected because the data rate R_b for a link is represented by $(R_{b_{local}}^{-1} + R_{b_{long}}^{-1})^{-1}$, where $R_{b_{local}}$ and $R_{b_{long}}$ denote the data rates for intra-cluster communication and inter-cluster communication, respectively. In the experiment, both $R_{b_{local}}$ and $R_{b_{long}}$ are $(250\text{K}{\cdot}\log_2(1+\zeta\{= 8\}))^{-1}$ and thus R_b is 396 Kbps. The total traffic load $TL_1 + TL_2$ = 99 Kbps requires only $1/4 = 0.25$ of the time to be scheduled. However, we should also note that although the minimum scheduling length is the same for FP and VP, they in fact have different performance results on other metrics. To show that, we plot the flow assignment achieved by the cross-layer scheme with the different power/rate schemes in Fig.4. This figure clearly shows that all the flows for the first (second) session have their directions toward its destination CH_9 (CH_1) despite the rate/power schemes. But even given the same trend of the flow directions, with the two different schemes, our cross-layer scheme actually results in different flow assignments for both session 1 and session 2. When considered with the power consumption, it can be also observed that after the 100 iterations, the VP scheme gives the average transmit power of 0.62 for the columns (transmission modes) resulted. On the contrary, the FP scheme results in the transit power of $P_{max} = 1$ as its definition suggests. Thus, we could conclude that with a lower transmit power for each column, the VP scheme can lead to a lower power consumption than the FP scheme.

V. Conclusion

In this paper, we have presented the method how to jointly determine routing, scheduling and stream control problem with the objective of minimization of scheduling length in

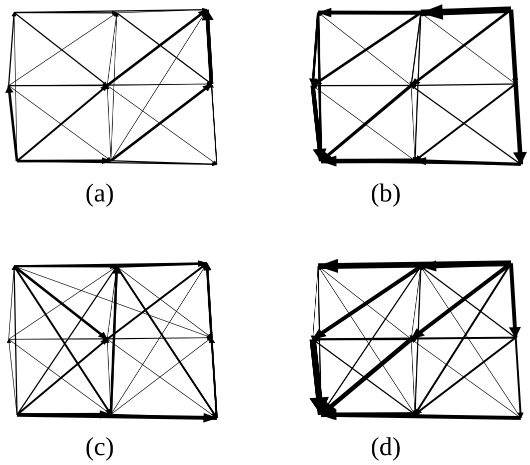


Fig. 4. Flow assignment results: (a) session 1 of FP, (b) session 2 of FP, (c) session 1 of VP, and (d) session 2 of VP.

scheduling-based multihop wireless sensor networks. Specifically, we have formulated the minimum scheduling length problem (MSLP) as a linear programming (LP), and its column generation (CG) subprogram as a integer programming (IP) or mixed linear integer programming (MLIP) problem. The experiment results show that the proposed cross-layer design approach can efficiently solve the MSLP problem with different power/rate adaptation schemes.

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