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Cooperative Multi-Hop Wireless Sensor-Actuator Networks: Exploiting Actuator Cooperation And Cross-Layer Optimizations

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***Abstract*—Delay and energy constraints have a significant impact on the design and operation of wireless sensor-actuator networks (SANETs). Furthermore, preventing sensor nodes from being inactive is very critical. The problem of sensor inactivity arises from the pathloss and fading that degrades the quality of the signals transmitted from actuators to sensors, especially in anisotropic deployment areas, e.g., rough and hilly terrains. Sensor data transmission in SANETs heavily relies on the scheduling information that each sensor node receives from its associated actuator. Therefore if the signal containing scheduling information is received at a very low power due to the impairments introduced by the wireless channel, the sensor node might be unable to decode it and consequently it will remain inactive.**

In this paper, it is proposed that each sensor node transmits its data to only one of the actuators. However all actuators cooperate and jointly transmit scheduling information to sensors with the use of beamforming. This results to an important reduction in the number of inactive sensors comparing to single actuator transmission for a given level of transmit power. The reduction is due to the resulting array gain and the exploitation of macro-diversity that is provided by the actuator cooperation. In order to maximize network lifetime and attain minimum end-to-end delays, it is essential to optimally match each sensor node to a particular actuator and find an optimal routing solution. A distributed solution for optimal actuator selection subject to energy-delay constraints is also provided.

Index terms: Heterogeneity, actuator-cooperation, macro-diversity, beamforming, delay-energy awareness, optimization.

I. Introduction and Related Literature

SANETs refer to a group of sensors and actuators linked by wireless medium to perform distributed sensing and actuation tasks. In such a network, sensors gather information about the physical world. Where actuators are usually resource-rich devices with higher processing and transmission capabilities, and longer battery life. Actuators collect and process sensor data and perform *actions* on the environment based on the information gathered.

Depending on the application there may be a need to *rapidly* respond to sensor input. Moreover, to provide right actions, sensor data must still be valid at the time of acting. Therefore, the issue of real-time communication is very important in SANETs since actions are performed on the environment after sensing occurs. Examples can be a *fire* application where actions should be initiated on the event area as soon as possible. Unlike wireless sensor networks where the central entity (i.e., sink) performs the functions of data collection and coordination, in SANETs, new networking phenomena called *sensor-actuator* and *actuator-actuator* coordination may occur. In particular, sensor-actuator coordination provides the transmission of event features from sensors to actuators. After receiving event information, actuators may need to coordinate with each other in order to make decisions on the most appropriate way to perform the actions. Each sensor node is associated with an actuator which is the destination of the sensor data. In order to prevent sensor data collisions, actuators transmit *time schedules* which coordinate sensor multi-hop transmission. Therefore each sensor after receiving the scheduling information from its associated actuator transmits its data at the right time slot. If the signal containing the scheduling information is received at a very low power due to channel impairments, the sensor node might be unable to decode it and consequently it will remain *inactive*.

To the best of our knowledge the potential problem of inactive sensor nodes in a SANET has not been investigated. Actuators receive sensor data in a multi-hop fashion and transmit the scheduling information to them in a single hop fashion. A sensor node needs to decode the received scheduling information from the actuator that it is associated with. This is in order to know its assigned time slot in which it should transmit its sensed data. However due to the impairments introduced by the wireless channel (signal degradation due to pathloss and fading), it is very likely that some sensor nodes, more likely the ones that are distant from the actuator, would not be able to decode their scheduling information. This is because some sensor nodes would probably receive the signal containing scheduling information at a very low Signal-to-Noise Ratio (SNR). Consequently they will remain inactive, a fact that could create some inactive zones in the sensing field. This would result to incomplete

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information reception, a situation that needs to be overcome for the uniform monitoring of the sensing field. A potential solution to this would be the use of positive and/or negative acknowledgments (ACKs and/or NACKs) with respect to the reception of scheduling information. In this fashion, for the sensor nodes that cannot decode their scheduling information, multi-hop transmission of their schedules can be employed. However this would result to a significant overhead burden in terms of time and energy waste of the sensor nodes, that can reduce their lifetime. Furthermore that type of solution would increase the complexity of the employed protocols.

For a sensor network with multiple sinks (sinks/actuators can be thought of similar entities for design purposes), the traffic generated by sensor nodes may be split and sent to different sinks [1], [4]. In the presence of multiple sinks, the problem of optimal sink selection with the aim of extending lifetime using anycast routing is studied in [5]. The authors propose a heuristic solution based on traffic volumes sent to different base stations to select an optimal base station. The proposed solution is based on flow splitting which follows different routes from a source to its selected destination. The provided solution is elegant in the essence of extending lifetime at routing layer. The only issue with this solution is the synchronization (MAC layer) among different nodes to which a source (sensor) directs its flow. They do not address this synchronization problem in the paper. Simulation results show better performance based on numerical data and the issues related to MAC and synchronization were elevated.

In cases, when there are multiple actuators and mapping between the sensors and actuators is not given, the joint problem of finding an optimal actuator and extending network lifetime with minimum end-to-end delay constraints is a challenging and interesting problem. This problem is relevant from both the application's and wireless networking perspectives. From an application requirement perspective, some real-time multimedia sensing applications (e.g., video surveillance) require to have all the traffic generated from a source sensor to be routed to the same actuator (it may follow different routes) so that decoding and processing can be properly completed because the information from the same source is highly correlated and dependent. From a wireless networking perspective, the actuator chosen as a sink could have a significant impact on the end-to-end delays which is a *hard* constraint [6] for sensor-actuator applications. This is because the end-to-end delays are topology dependent; actuator selection simply based on energy constraints can not guarantee optimal end-to-end delays, and therefore, it should be based on both delay-energy constraints. As a result, there appears to be a vital need to understand how to perform optimal routing to jointly achieve minimum end-to-end delay routes and optimize network lifetime in delay-energy constrained sensor-actuator networks.

In this paper, we propose a PHY, Routing and MAC solution with the aim of eliminating inactive zones in the sensing field, maximizing the network lifetime, and attaining minimum end-to-end delays. The problem of sensor inactivity can be effectively faced on the physical layer without increasing the protocol complexity and dissipating extra energy from sensor nodes. Actuators can cooperate and form a distributed antenna array, a concept that has been proposed for cellular communications [3]. The array jointly performs adaptive *beamforming* and distributes the time schedule to each sensor node. Sensors receive the schedule information at a much higher power due to the array gain that results from beamforming and to the exploitation of *macro-diversity* which is inherent to the distributed nature of a SANET. This results to a significant reduction in the number of inactive sensors for a given transmit *power level*. The cost is the need of Channel State Information at the transmitter (CSIT). It is shown by Matlab simulations that this effectively faces the problem of inactive zones. It is then proposed that each sensor node transmits its data to only one actuator. A sensor selects an actuator which is *minimum* number of hops away. *Note* that this actuator selection is just to decide a terminal point for sensor data transmissions and *multi-path* routing is actually used to transmit data between a sensor and its associated actuator. An advantage of setting min. hop criteria for actuator selection is that the lower-tier (sensor-actuator coordination level) of our heterogeneous network can be organized into clusters, where each cluster is centrally managed by an actuator. It is also shown that the flow routing with energy constraints can be modeled as a non-linear programming optimization problem (NLP). We use a relaxation to optimize the flow routing towards this actuator to extend network lifetime. We then propose to use an adaptive TDMA like MAC (that corresponds to the routing solution) to avoid the problem of synchronization during flow splitting and to meet the delay criteria for SANETs.

The organization of this paper is as follows. In Section II, we describe the Signal and network model under consideration. In Section III, the details of the Actuator to Sensor transmission schemes are presented. The advantages of cooperative Actuator transmission in terms of elimination of inactive zones in the sensing field are discussed and evaluated. Section IV details the design criteria of the proposed routing protocol and optimization obtained in this direction. In Section V, we conclude the paper and outline the future directions.

II. Signal and Network Model

A static 3-tier wireless sensor-actuator network with N sensor nodes, M actuators nodes, and B Base Stations is considered as shown in Fig. 1. Each sensor and actuator is equipped with an omnidirectional antenna. Actuators are inter-connected via a backhaul network (wireline or wireless). It is assumed that an equal number of sensors K is assigned to each actuator, so as $M \times K = N$.

Channel Model: A sensor node can decode a transmission from a neighboring sensor successfully if the experienced

SNR or SINR (in the case of CCI) is above a certain threshold. The channel between the i^{th} sensor node and the j^{th} actuator is

$$h_{ij} = \Gamma_{ij}\sqrt{\beta d_{ij}^{-\alpha}\gamma_{ij}} \qquad (1)$$

where d_{ij} is the distance in km of the i^{th} sensor and the j^{th} actuator. α is the path-loss exponent and β the path-loss constant. γ_{ij} is the corresponding log-normal coefficient which models the large-scale fading (shadowing), $\gamma_{dB} \sim \mathcal{N}(0\,dB, 8\,dB)$, and Γ_{ij} is the complex Gaussian fading coefficient which models the small-scale fading, $\Gamma \sim \mathcal{NC}(0,1)$. The pathloss constant and exponent are chosen according to the COST-231 model, where actuator height is assumed to be $10\,m$ and sensor node height $10\,cm$.

Neighborhood Relation Model: Given is an $(N+M+B) \times (N+M+B)$ neighborhood relation matrix R that indicates the node pairs for which direct communication is possible. We will assume that R is a symmetric matrix, i.e., if node i can transmit to node j, then j can also transmit to node i. For such node pairs, the $(i,j)^{th}$entry of the matrix R is unity, i.e., $R_{ij} = 1$ if node i and j can communicate with each other; we will set $R_{ij} = 0$ if nodes i and j cannot communicate. For any node i, we define $\mathcal{A}_i = \{j : R_{ij} = 1\}$, which is the set of neighboring nodes of node i.

Coordination and Relaying: The sensor-actuator network is deployed in a remote location. Sensors do the application dependent sensing and transmit their readings in a multi-hop manner to the actuators. Thus, each sensor node acts as a forwarder of data from other sensor nodes in the network. The actuators react on the environment based on the readings from the sensors and also forward (relay) this information to the Base Stations (using backhaul communication). Some in-network aggregation techniques could be applied at this stage if data is correlated. In this study, we assume that there is no energy constraints for actuators (infinite or rechargeable energy source).

III. Actuator to Sensor Transmission Schemes

In this section, three different actuator-to-sensor transmission schemes are presented together with their analysis and performance evaluation. Actuators can all transmit at the same frequency and therefore interfere with each other. They can also transmit at different frequencies in order to avoid interfering with each other at the cost of higher frequency reuse factors.

A. Transmission at a single frequency (Reuse Factor 1)

In this case, each actuator communicates with the sensor nodes that are assigned to it. The actuator broadcasts a packet containing scheduling information, for the sensors nodes attached to it, at the same frequency. Each sensor node receives together with useful scheduling information, co-channel interference (CCI) from other actuators. The received signal of the sensor node i is

$$y_i = h_{ij}\sqrt{P_j}x_j + \sum_{k \neq j} h_{ik}\sqrt{P_k}x_k + n \qquad (2)$$

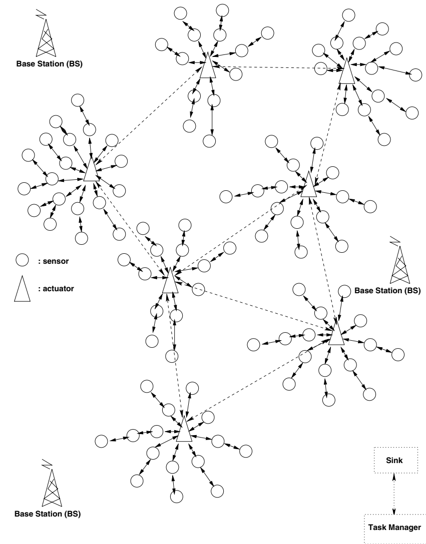

Fig. 1. Architecture of SANETs.

where $i = 1, 2, ..., K$, h_{ij} is defined in (1), j is the actuator that the sensor i is assigned to, P_j is the transmit power of each actuator, n is the additive white Gaussian noise (AWGN) component with power σ^2, and x_j is the transmitted scheduling information of actuator j. Throughout this paper it is assumed that all actuators transmit on the same power level. It is also assumed that $\mathrm{E}\left\|\mathrm{x_m}\right\|^2 = 1$. The packet x_j contains the schedules of all sensor nodes attached to actuator j. $\sum_{k \neq j} h_{ik}\sqrt{P_k}x_k$ represents the detrimental CCI term. Therefore, the Signal-to-Interference-Noise Ratio (SINR) of a sensor node i is

$$SINR_i = \frac{\left\|h_{ij}\right\|^2 P_j}{\sum_{k \neq j}\left\|h_{ij}\right\|^2 P_k + \sigma^2} \qquad (3)$$

If $SINR_i$ is below a certain threshold T $(SINR_i < T)$, sensor node i is unable to decode its scheduling information and therefore it is unable to resolve when to transmit its sensed data. Thus, it will remain inactive.

The advantage of this scheme is that each actuator, in order to distribute sensor scheduling information, broadcasts a packet that contain all sensor schedules. Therefore, in one time slot, all schedules are distributed. However, each sensor needs to go through all the contents of the scheduling packet in order to find its own schedule, a fact that increases decoding complexity. The main disadvantage is that some sensor nodes might remain inactive as described above.

B. Transmissions at different frequencies (Higher Reuse Factor)

In this case also, each actuator communicates with the sensor nodes that are associated with it. Each actuator broadcasts its scheduling information at a different frequency. This eliminates CCI at the cost of a higher frequency reuse factor (RF). The received signal at the sensor i is then

$$y_i = h_{ij}\sqrt{P_j}x_j + n \qquad (4)$$

where $i = 1, 2, ..., K$. The Signal-to-Noise Ratio (SNR) of a sensor node i is

$$SNR_i = \frac{\|h_{ij}\|^2 P_j}{\sigma^2} \tag{5}$$

The advantage of this scheme comparing to the frequency reuse factor 1 is the elimination of CCI. CCI degrades the received SNR and therefore increases the probability of sensor inactivity. By using different frequencies for each actuator, the number of inactive sensors is decreased for a given level of transmit power.

C. Actuator Cooperation (Joint Beamforming)

In this scenario, the actuators are assumed to be interconnected via high speed backhaul links (wireline or wireless). After an initial handshake between a sensor and its associated actuator (min. hop fashion, more details on this assignment are provided in Section IV), each actuator transmits a training sequence. Then each sensor estimates the channel between itself and all the actuators, and it transmits this set of channel coefficients to its associated actuator in a multi-hop fashion. Therefore, the Transmitter Channel State Information (CSIT) is obtained. Furthermore, each actuator determines the schedules for its associated sensors. Actuators exchange their local CSIT and their scheduling information via the backhaul links, and jointly perform Maximal Ratio Combining (MRC) beamforming in order to transmit the scheduling information to each sensor. Hence, actuators form a distributed antenna array. The transmission of the scheduling information is done in a Round-Robin fashion and at the same frequency. Each sensor has a channel vector $\mathbf{h}_i = [h_{i1}, h_{i2}, ..., h_{iM}]$. In order for the per-actuator power constraint to be satisfied, each actuator j transmits to sensor i

$$A_{ij} = \frac{h_{ij}^*}{\|h_{ij}\|} \sqrt{P_j} s_i \tag{6}$$

The received signal of the sensor node i is then

$$\begin{aligned} y_i &= \textstyle\sum_{j=1}^{M} h_{ij} A_{ij} + n \Rightarrow \\ y_i &= \textstyle\sum_{j=1}^{M} \|h_{ij}\| \sqrt{P_j} s_i + n \end{aligned} \tag{7}$$

where $i = 1, 2, ..., N$ and s_i is the schedule assigned to sensor node i. It is assumed that $E \|s_i\|^2 = 1$. Thus the SNR of the sensor node i in the case of equal power transmission is

$$SNR_i = \frac{P \left(\sum_{j=1}^{M} \|h_{ij}\| \right)^2}{\sigma^2} \tag{8}$$

Joint beamforming enhances the received SNR due to the array gain and the exploitation of macro-diversity which is inherent in a SANET. Therefore, this scheme provides a robust way of minimizing sensor inactivity. This is achieved at the cost of CSIT at the actuators. Furthermore, multiple time slots are needed in order to deliver the schedule to all sensor nodes, since actuators transmit to one sensor node at a time.

D. Performance Evaluation

The performance of the aforementioned transmission schemes is evaluated in terms of the number of inactive sensors that results from each transmission scheme. A number of sensors is deployed uniformly in a hexagon with a radius of 1 km. Three actuators are assumed at the three vertices of the hexagon separated by an angle of 120°. Actuator antennas are consider to have a gain of 12 dB (gain on the elevation), whereas, sensor node antennas have a gain of 1 dB. Through Monte-Carlo simulation the average number of inactive sensors is calculated for each transmission scheme as a function of the actuator transmit power. Averaging is performed over sensor node positions and channel realizations. A sensor is assumed to be inactive if its received SNIR or SNR is below the threshold of 1 Watt. In figure 2 it is plotted the average number of inactive sensors versus the actuator transmit power for 1200 deployed sensors. It can be seen that for the power of -12 dBw inactive sensor zones are almost completely eliminated in the case of MRC beamforming. In the case of Reuse Factor 3 (RF3), inactive zones are eliminated when the transmit power is approximately 0 dBw and in the case of Reuse Factor 1 (RF1) the average number of inactive sensors saturates approximately at 0 dBw.

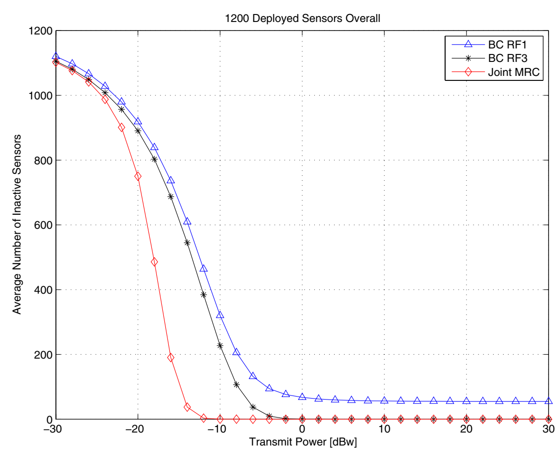

Fig. 2. Average Number of Inactive Sensors vs. Transmit Power.

In figure 3 it is plotted the average number of inactive sensors against the total number of deployed sensors for a different number of deployed sensor nodes, when actuators transmit power is -12 dBw. It can be clearly seen that the joint MRC beamforming scheme outperforms the simple Reuse 3 broadcasting, as the average number of inactive sensors is almost 0 for that power level.

In figures 4, 5 and 6, the probability of inactivity can be seen in the different areas of the hexagon for the three different transmission schemes considered, when actuators transmit power is -12 dBw. In the cases of RF1 and RF3

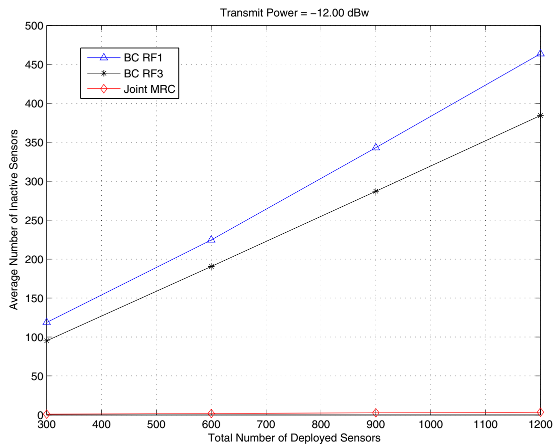

Fig. 3. Average Number of Inactive Sensors Vs. Total Number of Deployed Sensors.

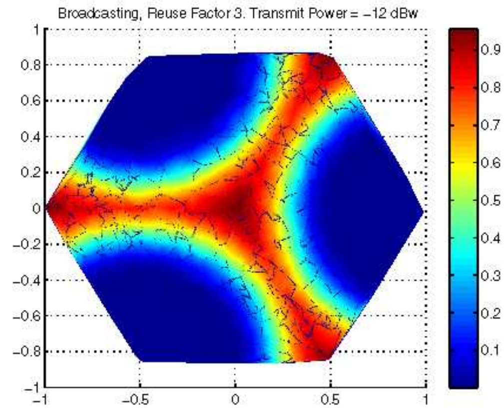

Fig. 5. Probability of Sensor Inactivity in the areas of the sensing field for the case of Reuse Factor 3 Schedule Broadcast Transmission.

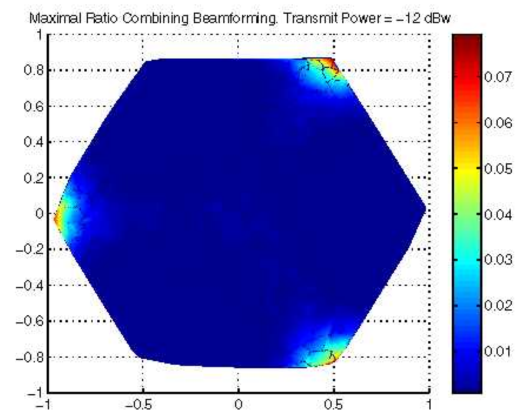

Fig. 6. Probability of Sensor Inactivity in the areas of the sensing field for the case of joint Maximal Ratio Combining Beamforming.

schedule broadcasting, the center of the topology experiences a significant probability of inactivity. In a real system implementation, this would result to an important loss of information. On the contrary, Joint beamforming almost eliminates inactive areas in the sensing field at this power level. This turns out to be a very effective actuator transmission scheme that greatly reduces the amount of transmit power needed to ensure very low sensor inactivity. This is because of the beamforming SNR gains and the macro-diversity gains that are provided by the spatially distributed transmitting actuators.

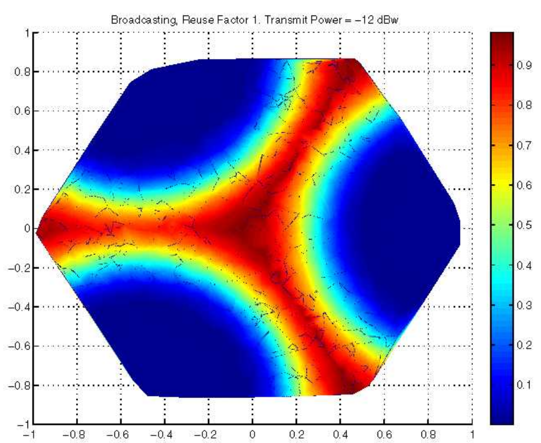

Fig. 4. Probability of Sensor Inactivity in the areas of the sensing field for the case of Reuse Factor 1 Schedule Broadcast Transmission.

IV. Sensor to Actuator Transmission Scheme

We consider a multi-hop routing at this level owing to the short transmission ranges of sensors. In the following, we detail several components of our proposed optimal flow routing protocol for SANETs.

Power Consumption Model: For a sensor node, the energy consumption due to wireless communication (i.e., receiving, transmitting, and idle state) is considered the dominant source in power consumption. The power consumed by a sensor node i in receiving can be modeled as $P_r^i = P_{rx} \sum_{j \in \mathcal{A}_i} f_{ji}$, where f_{ji} is the rate ($bits/s$) at which node j is transmitting packets toward node i. A typical value for the parameter P_{rx} is 50 nJ/b. If power consumed to send a packet is given by P_{tx} (a typical value for this parameter is 50 nj/b [7]), then the power consumed by a sensor node i in transmitting its data (both locally originated and forwarded packets) is $P_t\,(ij) = c_{ij} f_{ij}$, where c_{ij} is the power consumption coefficient for data transmission between sensor i and j. And f_{ij} is the total flow from sensor i to sensor j in $bits/s$. Also $c_{ij} = \alpha + \beta d_{ij}^m$, where α and β are constants, d_{ij} is the distance between the sensors i and j, and m is the path loss index. Typical values of α and $\beta$are $50nJ/b$ and $0.0013\,pJ/b/m^4$ (for $m = 4$), respectively [7]. We do not model the energy consumption in idle state at routing layer as it is effectively handled at the MAC layer [2]. Let $\sum_{1 \le l \le M} \lambda^{s_i A_l} = 1$ $(1 \le i \le N)$**,** where $\lambda^{s_i A_l}$ is a binary variable used for Actuator selection: if the data stream generated by a sensor i will be transmitted to actuator l, then

$\lambda^{s_i A_l} = 1$; otherwise $\lambda^{s_i A_l} = 0$. The actuator selection is based on *minimum-hop* criteria to solve the sensor-actuator binding process. We denote the resulting destination actuator for a sensor via the above mapping as $d(i)$. Therefore, we have $\lambda^{s_i d(i)} = 1$, and $\lambda^{s_i A_l} = 0$ for $A_l \neq d(i)$. Then a multi-hop and multi-path routing solution is proposed to route sensor data toward these actuators.

Optimal Multi-path flow Routing: We denote T as network lifetime at sensor-actuator coordination level, which (in this work) is defined as the time until a sensor node drains its energy. Then, we maximize lifetime T, s.t.

$$\sum_{r \neq i} f_{s_i s_r}^{s_i d(i)} + f_{s_i d(i)}^{s_i d(i)} - g_i \lambda^{s_i d(i)} = 0 \tag{9}$$

$$\sum_{r \neq i,k} f_{s_i s_r}^{s_k d(i)} + f_{s_i d(i)}^{s_k d(i)} - \sum_{m \neq i,k} f_{s_m s_i}^{s_k d(i)} = 0 \tag{10}$$

$$\Big(\sum_{f_{s_i s_r}^{s_k d(i)} \in F_{s_i s}} c_{s_i s_r} f_{s_i s_r}^{s_k d(i)} + \sum_{f_{s_i d(i)}^{s_k d(i)} \in F_{s_i A}} c_{s_i d(i)} f_{s_i d(i)}^{s_k d(i)} + \sum_{f_{s_m s_i}^{s_k d(i)} \in F_{s s_i}} p_{rx} f_{s_m s_i}^{s_k d(i)} \Big) T \leq e_i \, for \, (1 \leq i \leq N) \tag{11}$$

$$T,\ f_{s_i s_j}^{s_k d(i)},\ f_{s_i d(i)}^{s_k d(i)} \geq 0,\ 1 \leq i,j,k \leq N,\ i \neq j,\ k \neq j.$$

The set of constraints in (9) focuses on traffic flow generated locally at each sensor i: the locally generated bit rate $(i.e.,\ g_i)$ will be equal to the outgoing data flows from sensor i to actuator $d(i)$ via a single hop $\left(i.e.,\ f_{s_i d(i)}^{s_i d(i)}\right)$ or multi-hop $\left(i.e.,\ f_{s_i s_r}^{s_i d(i)}\right)$; otherwise, all flows corresponding to the source-destination pair $(s_i, d(i))$ must be zero. The set of constraints in (10) focus on the traffic that uses sensor i as a relay node: the total amount of incoming traffic $\left(i.e.,\ \sum_{m \neq i,k} f_{s_m s_i}^{s_k d(i)}\right)$ should be the same as the total amount of outgoing traffic $\left(i.e.,\ \sum_{r \neq i,k} f_{s_i s_r}^{s_k d(i)} + f_{s_i d(i)}^{s_k d(i)}\right)$ for each source-destination pair $(s_i, d(i))$. The set of constraints in (11) concerns energy consumption at sensor i: the energy consumption due to transmitting and receiving over the course of network lifetime should not exceed the initial energy supply e_i. Note that in (11) both flows generated locally at sensor i and those flows that use sensor i as a relay node are included. Finally the remaining set of constraints enforce that sensor i can only transmit all of its data to one actuator under any routing protocol, along with the logical restriction on the optimization variables $\lambda^{s_i d(i)},\ f_{s_i s_j}^{s_k d(i)},\ and\ f_{s_i d(i)}^{s_k d(i)}$. Note that $P_{rx},\ g_i,\ e_i,\ c_{s_i s_r},\ and\, c_{s_i d(i)}$ are all constants in this optimization problem. Also, $F_{s_i s}, F_{s_i A}, F_{s s_i}$ represents sets that contain flows: going out of sensor i to another sensor, from sensor i to the actuator, and from any sensor coming into sensor i, respectively. The formulation of optimal flow routing is a non-linear programming (NLP) problem, which is, unfortunately, NP-hard in general. The non-linearity component in the flow routing problem can be removed by multiplying the equations (9)-(11) by T and then use the linear substitutes $\left(V_{s_i s_j}^{s_k d(i)} = T\, f_{s_i s_j}^{s_k d(i)}\right)$, $\left(V_{s_i d(i)}^{s_k d(i)} = T\, f_{s_i d(i)}^{s_k d(i)}\right)$, and $\left(\mu^{s_i d(i)} = T\, \lambda^{s_i d(i)}\right)$. We now have a standard LP formulation that was transformed directly from the NLP problem. By their equivalence, the solution of this LP problem yields an upper bound to the basic flow routing problem. At MAC layer, we use an adaptive TDMA based MAC [2] that corresponds to the optimal routing solution. Using min. hop criteria for actuator selection organizes the heterogeneous sensor-actuator network into clusters which are centrally controlled by the associated actuators. Also, all the available routes from a sensor node to its assigned actuator are fairly used using multi-path routing subject to energy constraints through flow-splitting. The results on comparison between the analytical and actual (simulation) network-lifetime can be found in [7]. In a later version, we will provide a distributed algorithm (which resulted from the *dual* of Lagrangian of the above optimization) using an *exterior-to-interior* approach to achieve optimal flow routing with detailed implementation results.

V. Conclusions and Future work

First, this paper addresses the problem of inactive regions in the sensing field by letting actuators exchange their CSIT and jointly perform beamforming in order to deliver scheduling information to sensor nodes. The gains of cooperation were shown by simulating the average number of inactive sensors for the case of single actuator transmission and cooperative transmission. Since many applications require to have each source node send all its locally generated data to only one actuator for processing and the fact that the end-to-end delays in SANETs is a *hard* constraint, we jointly optimize the actuator selection and optimal flow routing subject to delay-energy constraints. This approach has near-optimal *performance* and is *practically implementable.*

We will take into consideration a dynamic actuator-assignment scenario to timely transport data in a *mobile* wireless sensor-actuator network.

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