VAA Formation Game for Cooperative Wireless Sensor Networks

(Invited Paper)

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***Abstract*—In this work we consider a Wireless Sensor Network (WSN), where nodes cooperate to send data to a remote sink. In particular, we assume that sensor nodes form Virtual Antenna Arrrays (VAAs) and use cooperative beamforming to transmit toward the sink. The VAA formation problem is formulated as a noncooperative game with complete information. In fact, on one hand cooperation greatly increases link capacity, but on the other, it introduces a certain overhead. The latter trade-off is analyzed resorting to a game theoretical approach in which sensor nodes aim at forming VAAs to maximise their own successful transmission rate, while keeping under control the energy consumed for the signaling within VAAs. Based on this analysis, we then introduce a communication protocol for VAA formation. Numerical results show the advantages of cooperation among nodes as well as the impact of considering a realistic communication protocol, accounting for packets losses, with respect to the ideal case achieved through the game.**

I. Introduction

Wireless sensor networks (WSNs) have recently gained increasing attention as practical technology being introduced to different applications. Most of these applications require to transmit the acquired data over long distances using transmission resources available only at sensor nodes. In this situation, direct transmission from a source node to a destination node over long distances often presents harsh obstacles mainly due to the large amount of energy required to establish a reliable transmission, thus fostering an inefficient use of the batteries.

Multiple-input multiple-output (MIMO) systems are well known for their capability to obtain high spectral efficiency in the presence of fading channels [1] [2]. However, the need to install multiple antennas in portable devices can be problematic for economic and practical reasons. To extend the advantages of MIMO systems to devices characterized by a reduced number of antennas, the idea of deploying a virtual MIMO (V-MIMO) architecture appears to be very promising. Cooperation among nodes is a fundamental aspect of V-MIMO systems, since nodes cooperate to create virtual antenna arrays (VAAs) [3]. In particular, one of the V-MIMO cooperation schemes is cooperative beamforming [4].

Despite its promise, the employment of VAAs poses several technical challenges mainly because of the large amount of signaling packets required to establish the cooperation among different nodes. Coalition formation has been investigated in [5], where the choice of the nodes is made on the basis of the overall energy consumption. The impact of the coalition size on the overall performance is investigated in [6].

A theoretical tool for studying and designing complex interactions among rational entities operating in a distributed manner is game theory. A huge number of works can be found in the literature where non-cooperative games are applied to model problems in communications (see, e.g., [7], [8]). [9] and [10] introduce a non-cooperative game, in order to design a resource allocation algorithm, maximising the energy efficiency of the system, evaluated in terms of bits correctly transmitted per Joule consumed.

The scope of this work is to design a communication protocol wherein sensors selfishly trade off the costs of forming VAAs and exploiting the energy left available in their own battery. In particular, inspired by [11], a non-cooperative game is applied to derive the best VAA organization. Numerical results, derived through simulations, show the advantages of cooperation among nodes as well as the impact of considering a realistic communication protocol.

II. Reference Scenario

The WSN under consideration is composed of N sensor nodes, equipped with a single ideal isotropic antenna and randomly distributed over a given area (see Fig. 1). The environmental parameters measured by sensors are sent to N_s sinks through a query-based communication protocol, where sinks periodically send a *query* to the nodes and each node transmits the data to the sink from which it receives the largest received power. Compared to sensor nodes, sinks may use a larger transmit power, so that each of them may trigger nodes in a large geographic area. Due to the limited transmit power and constraints in terms of energy consumption, sensor nodes

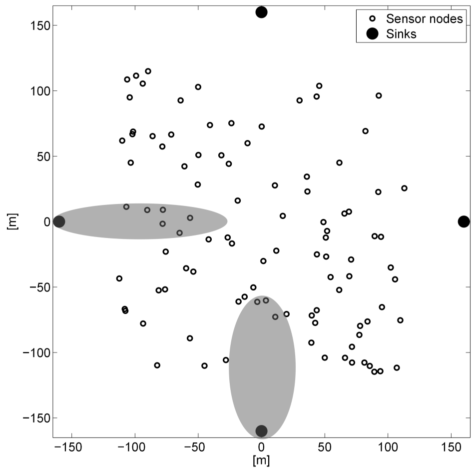

Fig. 1: Reference scenario.

may need to cooperate to reach the final sink with a given reliability. Towards this goal, sensors are organized in clusters to send data to the relevant sink, with up to $N_{\rm s}$ clusters of nodes formed at a time, one per sink. We assume that nodes will autonomously decide to act as sources if the measured data is sufficiently different from the one previously sent. Each *source node* takes advantages of a subset of nodes belonging to the same cluster, called *cooperating nodes*, acting as a VAA together with the associated source. Accordingly, denoting with $\mathcal{N}_i$, $i = 1, .., N_{\rm s}$, the set of nodes belonging to the i-th cluster, and with $\mathcal{M}_i$, $i = 1, .., N_{\rm s}$, the set of source nodes in cluster i, we have that $\sum_{i=1}^{N_{\rm s}} \mid \mathcal{N}_i \mid \leq N$ and $\mathcal{M}_i \subseteq \mathcal{N}_i$.

The considered node-to-sink channel model can be represented by the following channel transfer function

$$h_n = \frac{1}{\sqrt{k_0 d^{-\beta} s}} f, \; n = 1, ..., N \tag{1}$$

where k_0 is the reference pathloss, d is the distance between the transmitter and the receiver, β is the pathloss exponent, s is the log-normally distributed shadowing component and f is the fading component which follows circularly-symmetric complex normal distribution. For the sake of simplicity, the non-cooperative game considers only pathloss component, because shadowing and fading components are less influential, but complicate the formulation of the game.

III. Game Description

In this section, the main objective is to derive a noncooperative game model for the WSN described in Sec. II, in which the sensor nodes aim at forming VAAs to maximize their own successful transmission rate. To this end, sensor nodes are coerced to behave as self-interested agents in a social network (SN) in which users can create relationships to share contents or services. More in details, we treat sensors' transmit power as the contents that can be shared among users in an SN, while the relationships established to share those contents model the VAAs structure within the cluster. The final scope of this work is to design a communication protocol wherein sensors selfishly trade off the costs of forming VAAs and exploiting the energy left available in their own battery [11]. The outcomes of the strategic interactions among agents will be investigated as a Nash equilibrium (NE) problem which may lead to alternative distributed algorithms that present advantages in term of robustness of convergence, scalability, and required quantity of message passing [12]. It is important to note that sensor nodes are not really playing a game; rather the game theoretical analysis is used to study the possible outcomes of the strategic interactions among nodes and implement algorithms that achieve suitable steady solutions.

Before introducing the strategic game that models the interactions among the nodes, let us introduce the vector $\mathbf{g}_m \triangleq (g_{m,\ell})_{\ell \in \mathcal{N}, \ell \neq m}$, where $g_{m,\ell} = 1$ if node m wishes to form a VAA with node ℓ, and $g_{m,\ell} = 0$ otherwise. Analogously to what is proposed in [11], we assume that the cooperating nodes cannot refuse a VAA formation request and that cooperation is always reciprocal. In other words, cooperation between two sensors can be unilaterally established at the condition that the sensor requesting cooperation will afford the entire *virtual* cost to maintain this relationship. Thanks to this mechanism, each node can impose the collaboration to the other nodes at the condition that the benefit it obtains is greater than the cost per cooperating node established by the designer. Under this assumption, the cooperation status between nodes m and ℓ is

$$\bar{g}_{m,\ell} = \begin{cases} \max\{g_{m,\ell}, g_{\ell,m}\} & m \neq \ell \\ 1 \quad m = \ell \end{cases} \tag{2}$$

where nodes m and ℓ are called *neighbors* if $\bar{g}_{m,\ell} = 1$. Signal to Noise Ratio (SNR) can be expressed by

$$\gamma_m(\mathbf{p}, \bar{\mathbf{g}}_m) \triangleq \frac{b_0^2}{\sigma^2} P_{\text{tot},m}(\mathbf{p}, \bar{\mathbf{g}}_m), \tag{3}$$

where b_0^2 is the mean pathloss within a cluster, σ^2 is the noise power and $P_{\text{tot},m}$ is the total power of cooperative transmission defined as

$$P_{\text{tot},m}(\mathbf{p}, \bar{\mathbf{g}}_m) \triangleq \sum_{\ell \in \mathcal{L}_m \cup \{m\}} p_\ell \tag{4}$$

We can now highlight the following.
1) Each node in the WSN is considered as a player of the VAA formation game playing strategy $\mathbf{t}_m = (p_m, \mathbf{g}_m)$.
2) Each sensor, can form a VAA with the nodes that are only one hop away from it in the connectivity graph (neighbors).
3) The benefit obtained by generic sensor m is a strictly concave and monotonically increasing function of the SNR level γ_m. A convenient choice for the benefit function is

$$v_m(\mathbf{p}, \mathbf{g}) = \log\left(1 + \frac{b_0^2}{\sigma^2} P_{\text{tot},m}(\mathbf{p}, \bar{\mathbf{g}}_m)\right), \tag{5}$$

i.e., the mth VAA's achievable information rate.
4) Since each node should prevent the adoption of a too high transmit power, due to the battery limitation, a linear cost of $\lambda \in \Re^+$ per unit of energy a node produces is introduced.
5) Finally, the bigger the coalitions size, the higher the number of signaling packets, introducing collisions and excessive

overheads that may increase waste of energy. Thus, each node is assumed to incur in a VAA formation cost k for each VAA formation request he produces.

Based on the above-mentioned observations, the VAA formation game is defined by the tuple $\mathcal{G} \triangleq \{\mathcal{N}, \mathbf{t}_m, u_m\}$, where players are the WSNs in $\mathcal{N}$, the strategy profile of the mth player is $\mathbf{t}_m = (p_m, \mathbf{g}_m)$ and its utility function is

$$u_m(\mathbf{t}_m, \mathbf{t}_{-m}) \triangleq v_m(\mathbf{t}_m, \mathbf{t}_{-m}) - \lambda p_m - k||\mathbf{g}_m||_1, \quad (6)$$

where $\mathbf{t}_{-m}$ is the vector collecting the strategies played by all the players but the mth. Note that the proposed game is equivalent to the one originally analyzed in [11] for SNs. The solution concept for this game is the well-known Nash equilibrium (NE), i.e., a strategy profile $\mathbf{t}^* = (\mathbf{p}^*, \mathbf{g}^*)$ such that

$$u_n(\mathbf{t}_n^*, \mathbf{t}_{-n}^*) \geq u_n(\mathbf{t}_n, \mathbf{t}_{-n}^*), \quad \forall n \in \mathcal{N}. \quad (7)$$

In [11], the authors discovered that, when the size of the population is sufficiently high, every strict noncooperative equilibrium of this game can produce either a symmetric topology where all users produce the same amount of contents and have the same number of neighbors or a hierarchical structure with only two possible levels of contents production, i.e., a high level and a low level. Moreover, the only symmetric profiles that could emerge at the NE are either only composed by singletons or with all nodes cooperating between them.

Though, the case of symmetric profile at the equilibrium does not satisfy the desired features of the VAA formation strategy. In fact, the complete graph would cause excessive signaling to form the VAAs, while the solution of only singletons would require an excessive power to those nodes with poor battery status. On the other side, equilibria with asymmetric profiles fits with the requirement of having different transmit powers due to the heterogeneous levels of energy left available at the sensor nodes. At the equilibrium point, a node with low transmit power can only cooperate with a node presenting a high transmit power [11], which is suitable for our VAA structure where the sensor nodes with high energy availability can help the sensors with a poor battery status. Hence, from now on, we will refer to the sensors with low transmit power and high transmit power as *weak nodes* (WNs) and *potential helpers* (PHs), respectively. Unfortunately, all these appealing features are frustrated by the so-called *law of the few* [11]. According to this, if the user's benefit depends only on the total quantity of acquired contents (i.e. contents are perfectly substitutable), the number of potential helpers will vanish as N tends to infinity. Consequently, the proposed game theoretical model will produce an useless structure for large VAAs.

A. Dixit-Stiglitz Preference Model

A viable solution to this problem is to modify the benefit function of the sensors. In fact, the information rate in (5) considers the transmit power shared by different nodes of the VAA as perfectly substitutable, i.e., only the total amount of power (4) used for transmitting signal s_m determines the benefit of the mth node. The main idea is that cooperation among nodes might be fostered via a modified benefit function that models the users' interest in taking advantages from a *variety* of power sources. Hence, instead of assuming the perfect substitutability of the power, we use the *Dixit-Stiglitz* preference model [13], which enables the possibility of appreciating the variety of the power sources, yielding the concept of *effective power*

$$P_{\mathrm{eff},m}(\mathbf{t}_m, \mathbf{t}_{-m}) \triangleq \left(p_m^\rho + \sum_{\ell \in \mathcal{L}_m(\bar{\mathbf{g}}_m)} p_\ell^\rho\right)^{1/\rho}, \quad (8)$$

where $\mathcal{L}_m(\bar{\mathbf{g}}_m)$ is the set of neighbors of node m and $\rho \leq 1$ represents the node's appreciation for the variety of power sources. This appreciation increases as $\rho \rightarrow 0$, whereas disappears for $\rho = 1$, where (8) is equal to (4) indeed.

Based on the above-mentioned observations, a modified version of the VAA formation game is introduced, with

$$v_m(\mathbf{t}_m, \mathbf{t}_{-m}) = \log\left(1 + \frac{b_0^2}{\sigma^2} P_{\mathrm{eff},m}(\mathbf{t}_m, \mathbf{t}_{-m})\right) \quad (9)$$

being the new players's benefit which replace (5) in (6). We now discuss the properties of the equilibrium points obtained thanks to the Dixit-Stiglitz preference model.

B. Analysis of the Equilibrium Point

The proposed game is a particular case of the IPLF framework investigated in [11]. Here, it is worth recalling the following two major results.

1) Existence of the NE [11, Th. 1]: Pure Nash equilibria of the game always exist and each equilibrium belongs to one of the following types: *i)* a symmetric strategy profile in which each node personally consumes an amount of power $P_{\max} \triangleq \frac{1}{\lambda} - \frac{\sigma^2}{b_0^2}$, and no one forms any VAA; *ii)* an asymmetric strategy profile in which each node personally consumes an amount of power $p_m^\star$ strictly smaller than $P_{\max}$ and forms a VAA with at least one other player. Moreover, at the equilibrium we have

$$P_{\max} = \frac{1}{\lambda} - \frac{\sigma^2}{b_0^2} \leq \left(p_m^\star + \sum_{\ell \in \mathcal{L}_m(\bar{\mathbf{g}}_m)} p_\ell^\star\right). \quad (10)$$

Hence, if the cost λ is chosen so that $P_{\max}$ respects some minimum performance requirements, the resulting equilibrium point will guarantee those requirements too.

2) Core-periphery structure of the NE [11, Th. 2-3]: In an asymmetric equilibrium, when $N = |\mathcal{N}| \rightarrow \infty$ and given λ, k, and ρ, we can classify the nodes into two categories: PHs and WNs. PHs transmit with a power P_{ph} and ask for collaboration only to other $N_{\mathrm{p,p}}(\mathbf{t}^*)$ PHs while WNs transmit with a power P_{wn} and ask for collaboration to $N_{\mathrm{w,p}}(\mathbf{t}^*)$ PHs. Moreover, the number of PHs $N_{\mathrm{ph}}(\mathbf{t}^*)$ is such that: *i*) $N_{\mathrm{ph}}(\mathbf{t}^*) < N_{\mathrm{wn}}(\mathbf{t}^*)$, where the latter is the number of WNs; *ii*) it grows at the same order as the entire population, i.e.

$$\lim_{N\rightarrow\infty} \inf_{\mathbf{t}^* \in \Phi_{\mathcal{N}}} \frac{N_{\mathrm{ph}}(\mathbf{t}^*)}{N} = \eta \quad (11)$$

where η is a constant and $\Phi_{\mathcal{N}}$ is the set of Nash equilibria for a population of size N. As apparent from (11), the law of the few is not valid when the Dixit-Stiglitz model is accounted for, thus making the game theoretical model appealing for a cooperative WSN scenario.

IV. Communication Protocol

Relying on the design guidelines obtained with the game theoretical analysis of Section III, this section describes the different steps of the communication protocol required to get the cooperative beamforming transmission. For what concerns the access to the channel, a contention-based protocol, as the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol defined by the IEEE 802.15.4 standard, is used for data transmissions, if not otherwise specified.

A. Cluster Formation

Each sink sends a query, using a power much higher with respect to the maximum power at which nodes may transmit. All nodes triggered by a given sink join its cluster. If more than one query is received by a node, the latter selects the sink from which it receives the highest power. Every node $m \in \mathcal{N}$ sends a short packet, including its battery level e_m, towards the sink. In turn, the sink collects all the battery levels in the vector $\mathbf{e} \triangleq [e_1, \ldots, e_N]^T$, whose elements are sorted in increasing order. Since at this stage lots of nodes will attempt to transmit a packet, a high maximum number of retransmissions is allowed, to avoid packets loss. This step makes each sink aware of the number of nodes belonging to its cluster and of their battery levels. The latter are used as input to run the game at the sink and compute the VAA formation parameters according to the following procedure.

1) The sink computes the vector of maximum powers at which each sensor may transmit as $\overline{\mathbf{p}} = \mathbf{e}P_{\max}$, where $P_{\max}$ is expressed by (10).

2) A minimum number of WNs is selected as $N_{\rm wn} = N/2$.

3) According to the value of $N_{\rm wn}$, the two levels of power must satisfy the following requirements: $P_{\rm wn} \leq \overline{\mathbf{p}}(0)$ and $\overline{\mathbf{p}}(0) < P_{\rm ph} \leq \overline{\mathbf{p}}(N_{\rm wn})$.

4) The sink checks if there exists an equilibrium point of the game $\mathcal{G}$ that satisfies the requirements of Step 3 (for the sake of brevity we omit the details of the algorithm). If the equilibrium exists, the sink broadcast $\overline{\mathbf{p}}(0)$, $\overline{\mathbf{p}}(N_{\rm wn})$ and $P_{\rm ph}$, together with the values $N_{\rm w,p}$ and $N_{\rm p,p}$ that guarantee the existence of the equilibrium, and the procedure ends. If the equilibrium does not exist, $N_{\rm wn}$ is increased by 1 and steps 3 and 4 are repeated.

B. VAA Formation

Once the clusters are established, a subset of the triggered nodes will act as source nodes. For the sake of simplicity we consider the sources to be WN. To form its VAA, each source transmits in broadcast a cooperation request packet. Nodes, sources or not, receiving such a packet, reply with an unicast cooperation reply packet to the source, including the status of its battery, i.e., if it is a WN or a PH. At this point each source selects its cooperating nodes, among those from which the cooperation reply has been received. Since each source knows the optimum number of PHs, $N_{\rm ph}$, and WNs, $N_{\rm wn}$, it should cooperate with, in case the number of replies from PH is larger than $N_{\rm ph}$, or number of replies from WNs is larger than $N_{\rm wn}$, nodes are selected according to the largest power received. Once the set of cooperating node, $\mathcal{L}_m$, is defined by source m, it sends to such nodes an acknowledge (ACK), to let them know they belongs to its VAA and to provide a time scheduling that will be used in the VAA to avoid collisions among nodes of the same VAA. Cooperation request and reply are sent using CSMA/CA.

C. Cooperative Beamforming

Once the VAA formation is done, each source performs CSMA/CA to transmit its data. When the channel is found free, sources broadcast their data so that each node in their VAA has a copy. This transmission is also exploited as a trigger for the next phase in which the cooperating nodes transmit pilots towards their sink using a scheduled time division scheme (each node has an assigned time slot) defined during the VAA formation. These pilot packets are used for channel estimation. Upon the reception of these pilot packets, the sink replies with an ACK packet containing the channel estimation. Immediately after the ACK packet is received by the VAA members, they calculate their transmission weight and the cooperative data transmission occurs.

V. Numerical results

Numerical results are obtained through simulation and the chosen metrics are SNR and energy consumption of cooperative transmission. $N = 100$ sensor nodes are uniformly distributed over $130m \times 130m$ observation area, surrounded by $N_S = 4$ sinks located $30m$ from the edges. Channel parameters are $k_0 = 1260$, $\beta = 3$, the noise power $\sigma^2 = -110dBm$ and the duration of packet transmission $T_{packet} = 0.8ms$.

Given that all the nodes in a VAA set their transmit weight in a proper way ($w_\ell = e^{-jarg\{h_\ell\}}$), the overall SNR of the cooperative transmission is defined as $\eta(\mathbf{p}, \bar{\mathbf{g}}_m) \triangleq \frac{1}{\sigma^2} \sum_{\ell \in \mathcal{L}_m \cup \{m\}} p_\ell |h_\ell|^2$, whereas the energy consumption of a cooperative transmission is $E = T_{packet} \sum_{\ell \in \mathcal{L}_m \cup \{m\}} p_\ell$.

We compare the case where no cooperation is present with the NE of the game, and the case in which the presented communication protocol is employed. In this way we show both the advantages of cooperative transmission and the extent to which the NE can be achieved in a realistic environment.

Fig. 2 shows η as a function of parameter ρ. First, we can observe that the case where there is no cooperation achieves the worst performance by far. This is of course expected, since the transmission power of a source is always lower than the total transmit power of the VAA which includes the source.

Looking at the ideal case, represented by the black line, it can be observed that the average SNR decreases with ρ. According to Dixit-Stiglitz model, increasing ρ will decrease the source interest for cooperation, leading to smaller VAAs thus further leading to lower average SNR.

The communication protocol is evaluated in different settings. Considering nodes with two levels of receiver sensitivity,

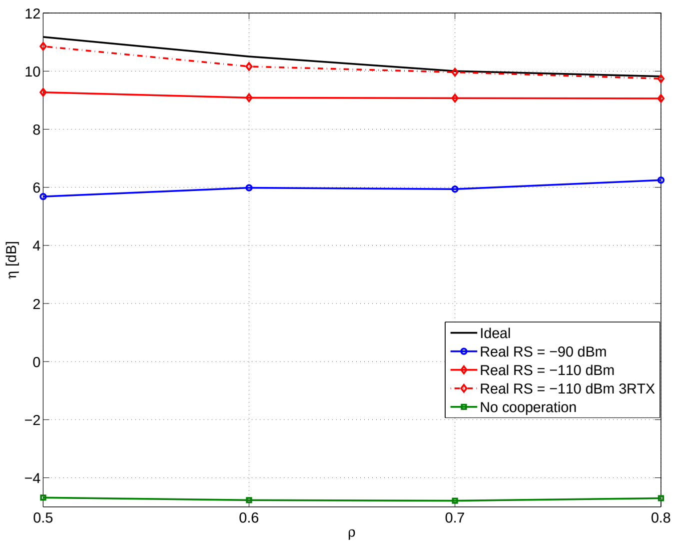

Fig. 2: Average SNR of cooperative transmission.

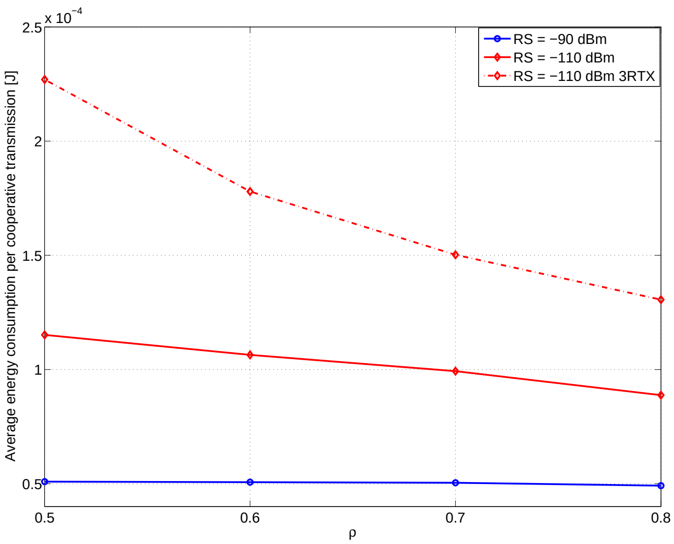

Fig. 3: Energy consumed by cooperative transmission.

we evaluate the impact of connectivity on the performance. On one hand lower receiver sensitivity, RS, means higher number of neighbors, thus higher number of potential cooperating nodes, but, on the other hand, it also increases the collision probability. Observing the results it can be concluded that the former effect is more important as decreasing receiver sensitivity leads to better performance.

There are several protocol parameters which can be modified in order to trade off between the generated overhead and the proximity to the ideal case. For example, by setting the maximum number of retransmissions of cooperation request to 3, the protocol achieves almost the same performance as in the ideal case. We can conclude that at cost of certain amount of overhead, the solution of the game can be replicated.

Fig. 3 shows the energy consumed by the cooperative transmission as a function of parameter ρ. It can be observed that having higher ρ decreases the energy consumption, since less nodes are involved in the VAA. The curve representing higher receiver sensitivity is practically not affected by ρ, since the number of cooperating nodes is mostly limited by the connectivity. In fact, the curves representing lower receiver sensitivity have steeper slope because the communication protocol is following the game solution.

VI. Conclusions

We presented a cooperative communication scheme for WSN in which game theory is employed to derive VAA organization. A non-cooperative game is balancing the performance gain achieved through cooperative beamforming with the increase in energy consumption due to required overhead. We show that by setting parameter ρ of the Dixit-Stiglitz preference model, this trade-off can be tuned. Namely, decreasing ρ increases the SNR at a cost of energy consumption, and vice-versa. We also introduced a communication protocol which aims at realizing the VAA structure suggested by the game. It is shown that by properly setting the parameters of the protocol, such as the maximum number of retransmissions of cooperation request packet, game solution can be reached.

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