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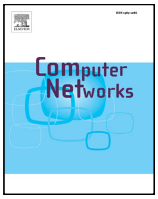

A practical cross layer cooperative MAC framework for WSNs[☆]

M. Sarper Gokturk[a,*], Ozgur Gurbuz[b], Murat Erman[c]

[a] *AirTies Wireless Networks, Istanbul 34394, Turkey*
[b] *Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul 34956, Turkey*
[c] *Vodafone Turkey, Istanbul, Turkey*

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ABSTRACT

The evolving Internet of Things is expected to enable realization of wireless sensor networks (WSNs) for a variety of applications. Energy efficiency and reliability are the key criteria for the success of WSNs of IoT. In this article, a cooperative medium access control (MAC) framework is proposed for improving the performance and energy efficiency of WSNs, while satisfying a given reliability constraint. The energy-reliability trade off is achieved through a relay selection and power assignment algorithm, which is implemented within the COMAC cooperative MAC protocol that enables the coordination of candidate relays, calculation of the decision metrics, selection and actuation of the relay nodes with optimal power levels for cooperation. The proposed cross-layer MAC framework is evaluated in terms of energy costs as well as network performance metrics, in terms of throughput, delay and overhead. It is shown that the network throughput can be improved significantly, while the energy consumption is reduced by at least two orders of magnitude as compared to standard Zigbee WSNs, at negligibly small overhead and computational costs.

1. Introduction

The term Internet of Things (IoT) refers to uniquely identifiable objects and their virtual representations in an internet-like structure. These objects can include any kind of goods, such as buildings, cars, trains, planes, machines, industrial plants, human beings, animals and plants or their body parts, all connected to form a smart environment [1]. While IoT does not assume a specific communication technology, in particular, wireless sensor networks (WSNs) will proliferate many applications and many industries [2,3].

The current WSN technology has matured on Zigbee, WirelessHART and ISA100.11a standards, which involve the basic wireless communication and networking functions from IEEE 802.15.4 [4]. However, the success of IoT will depend on the improved performance, mainly in reliability and energy efficiency performance of WSNs [5,6]. The reliable delivery of sensor data plays a crucial role in the WSNs of smart environments and IoT. The reliability requirements may vary depending on the application or the content of the data itself. For instance, for temperature monitoring in a smart home, a certain percentage of data loss can be tolerated for delivering temperature data within normal range; while a high temperature measurement must be delivered at very high reliability, since it can be the sign of a fire. In a health monitoring application, delivery of all the sensory data may require high reliability. Reliability, as one of the Quality of Service (QoS) parameters, can be measured in terms of Bit Error Rate (BER), Frame Error Rate (FER) or packet loss rate metrics. QoS provisioning in wireless networks is achieved via resource allocation [7], and resource allocation considering reliability has been an important problem in all types of wireless networks, such as third generation cellular systems [8]. For

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[*] Corresponding author. Tel.: +90 212 318 62 00.

E-mail addresses: sarper.gokturk@airties.com (M.S. Gokturk), ogurbuz@sabanciuniv.edu (O. Gurbuz), murat.erman@vodafone.com (M. Erman).

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WSNs, as much as reliability, energy consumption is also critical, since most of the sensor and wireless nodes are battery powered. Energy efficiency is fundamentally determined by the trade off between reliability and energy costs, both of which are dependent on employed wireless communication and medium access schemes.

The improvement of the wireless channel quality is beneficial, not only from the communications perspective, but also from the energy perspective, due to potential reduction in the energy costs of data transmission, reception, re-transmission(s) and interference. The quality of the wireless channel can be significantly improved by antenna diversity and multiple input multiple output techniques, as the receiver is provided with multiple copies of the original signal through independent fading paths, resulting in diversity gain [9–11]. However, deploying and implementing multiple antenna techniques on relatively small sensor nodes is a challenge for WSNs of smart environments. Hence, spatial diversity can only be achieved via cooperative communication. In this technique, known as *cooperative diversity*, the antennas of neighboring nodes, i.e., relays or cooperators (the two terms are used interchangeably throughout the paper) around a sender node are utilized and multiple nodes transmit cooperatively to a destination node forming a virtual antenna array, which results in the desired diversity gain [12].

Cooperation has been shown to provide better energy efficiency than that of direct transmissions, in particular for cases where source-destination channel is not good enough for direct transmissions [13,14]. Energy saving is achieved as packet retransmissions from the source node are avoided through cooperative transmissions, which also boost the signal reception as a result of diversity gain. Distributed implementation of cooperative communication imposes extra challenges on system design, because the energy savings provided by cooperative transmission may degrade as a consequence of the energy cost incurred by the cooperation initiation stage, where the cooperation set is formed. The amount of energy savings provided by cooperation depends on how many and which relays are selected for cooperation and how much transmit power is assigned to each relay. While transmit power allocation is related to the physical layer, initiation and coordination of cooperation is controlled by the medium access control (MAC) layer.

Cooperative MAC design for WSNs requires a cross-layer approach, which differs significantly from the conventional MAC protocol design. Realizing cooperative communication among nodes in a network requires the coordination of multiple network layers, and calls for essential modifications on the design of the layers of the protocol stack. In particular, the physical layer, which handles bit level transmissions over the communication medium, the medium access layer, which handles shared access to the communication medium, and the network, or the routing layer, which routes data across the network, should be designed jointly [15–17]. Conventional MAC protocols aim to coordinate and schedule the nodes' transmissions to minimize collisions and to reserve the medium to only a single user at a given time, frequency or code dimension [18]; while cooperation stems from the fact that possible relays overhear the transmissions of communicating entities and they transmit the overheard signal in cooperation with the source node [12]. The cooperative MAC requires mechanisms for selection, coordination and actuation of the cooperating nodes, and cooperative transmission of the information, all of which cause extra messaging [19], and increase in energy costs [13,14,19]. Therefore, cooperative MAC design requires a thorough evaluation of energy efficiency, quantifying how the performance gains brought by cooperation compare to the energy costs, while the QoS target is satisfied.

In WSN scenarios with low mobility, such as IoT in smart homes, fading is quasi static and the channel can be assumed to remain unchanged for multiple packet (frame) durations, where the average BER is the best metric to represent the reliability requirement. In this work, a cooperative MAC framework is proposed for improving the energy efficiency of such WSNs, and considering the BER as the reliability metric, an optimal relay selection and power assignment algorithm are implemented within the Cooperative Medium Access Control (COMAC) protocol in a distributed fashion. By detailed performance analysis, the COMAC framework is shown to provide significant improvements over the existing, standard WSNs based on Zigbee [4], by five to hundred times higher throughput, at least one and up to three orders of magnitude lower delay and two orders of magnitude smaller energy cost, which make the proposed framework pivotal for WSNs in IoT [3]. The contributions of this paper can be summarized as follows:

- The COMAC framework is presented as an energy efficient MAC framework for implementing cooperation with intelligent relay selection and actuation.
- Distributed relay selection and power assignment (D-CSPA) algorithm that minimizes energy costs while achieving reliability is implemented in the COMAC protocol.
- The candidate relays are coordinated, the relay selection metrics are calculated, and the optimal set of relays and their optimal power levels are determined in a distributed, iterative fashion with collision resolution.
- Significant energy savings are obtained by letting the nodes that are unfeasible for cooperation to go into sleep mode during the cooperation set formation process.
- Energy efficiency of the COMAC framework is evaluated realistically, considering the energy costs at both physical and MAC layers, as well as the computational energy costs of the algorithms, along with network performance metrics. Our detailed simulations depict the COMAC framework's promise for significant improvements in throughput and delay as well as significant energy savings, as compared to the state of the art WSNs.

The rest of the paper is organized as follows: Section 2 presents a summary of the related works on cooperative MAC. Section 3 includes the preliminaries, the relay selection and optimal power assignment algorithm, i.e., D-CSPA for a given BER requirement. Section 4 presents the proposed COMAC framework with Available to

COoperate (ACO) timer design, ACO collision resolution and cooperative sleep features to enable D-CSPA operation in an energy efficient way. Section 5 presents the performance of COMAC with D-CSPA with detailed simulations and Section 6 provides our conclusions.

2. Related work

In the literature, existing cooperative MAC protocols either rely on very complex physical layer models, which necessitate compromises at the MAC layer design leading to inaccurate performance analysis, or very simplistic physical layer models that obfuscate the underlying challenges on cross-layer MAC design and operation. In [20] and [21], comprehensive surveys on cooperative MAC protocols are provided. In [22], an adaptive method based on distributed timers is proposed to select and actuate the best relay among many possible relays. For densely deployed networks, this method requires a long period of silence (no transmission) during the relay selection epoch, which degrades the throughput performance considerably. In [23], cooperative transmissions are employed to provide diversity gain to a collision resolution protocol presented in [24]. In [25–27], the authors propose a cooperative MAC protocol that exploits randomized distributed space time codes (RDSTC) for opportunistic on-the-fly relay selection. The main shortcomings of the cooperative MAC protocols in the literature are that they either disregard the burden of MAC messaging [28,29] or they do not investigate the energy costs of actuating relays [25–27,30].

Relay selection problem for cooperative transmission has also been studied within a mathematical framework. In [31], a Markov decision process framework is proposed for adjusting the transmission powers and transmission probabilities in the source and relay nodes to achieve the highest network throughput per unit of consumed energy in a cooperative system that employs slotted Aloha as the MAC protocol. Furthermore, a decentralized partially observable Markov decision process model for selecting the relays to perform the cooperative retransmission is studied in [32].

QoS and fairness in WSNs have been investigated in [33], where the authors propose a slotted-aloha based ultra wide band (UWB) MAC protocol with cooperative retransmissions that provides differentiated QoS in networks with varying traffic classes. In [34], a simple MAC layer cooperation retransmission scheme that takes in account fairness is studied. Furthermore, in [35], the authors investigate the optimal cooperation strategies in the absence of coordination message passing between relays in order to maximize the system throughput and reduce the control packet overhead while considering the UWB unique properties such as fine ranging and immunity to small scale fading.

Whereas the above mentioned works rely on source initiated cooperative transmissions, the following works focus on receiver initiated cooperation. In [16], the authors study a cross-layer analytical model for the study of network coding based Automatic Repeat reQuest (ARQ) MAC protocols in correlated slow-fading environments, where two end nodes are assisted by a cluster of relays to exchange data packets. In [36], the authors study a collision avoidance mechanism, altruistic back-off, that aims to avoid collisions before the transmission of a beacon in receiver-initiated MAC protocols for WSNs. In [37], the authors propose a network-coding based cooperative ARQ MAC protocol for WSNs that coordinates the retransmissions among a set of relay nodes which act as helpers in a bidirectional communication.

Among our previous related works, [38] introduces the first version of the COMAC protocol, which enables cooperation with only a single relay, assuming that it is already known as the best neighbor for cooperation, and [39] presents a simple extension to support multiple relays, where the relays are selected randomly. In [40], COMAC with a single relay is implemented in a wireless model based predictive networked control system, and it is shown that by cooperation, even with a single relay node, the challenges of the wireless control problem can be alleviated and the performance of the industrial control network can be significantly improved. However, none of these works addresses the reliability-energy trade off, optimal relay selection or power assignment for energy efficiency. In [41], we have investigated the energy optimal joint relay selection and power allocation problem, considering cooperation in a wireless environment with high mobility, i.e., fast fading, where the channel conditions change several times within a frame duration. In that work, the reliability requirement reflecting the quality of the cooperative link is measured in terms of FER. The proposed algorithms in that work cannot be directly applied in WSNs with low mobility, where fading is slower, since the channel remains unchanged for a number of frames. For such channels, the link quality is best described by the average BER which is constant per frame. With the same reasoning, the solutions from [41] cannot be implemented in a MAC protocol designed for slow fading. In this work, the relay selection and power assignment algorithm is designed with BER as the reliability constraint, and the algorithm is implemented in the COMAC protocol along with additional energy saving features, resulting in an energy efficient cross layer framework for WSNs with low mobility.

3. Preliminaries: relay selection and power assignment with BER QoS

In this section, the optimal relay selection and power assignment problem and solution in [41] is revised after considering BER as the reliability constraint. The reader is may refer to [42] for the details of this formulation with BER requirement.

In the system model, we consider N relay nodes in the neighborhood of a source node, S, which communicates with the destination node, D, as shown in Fig. 1. N neighboring nodes can be arranged in $2^N - 1$ different possible cooperation sets (excluding the empty set, which represents direct transmission) to help the source. Let us consider the possible sets with r cooperators, which makes up $\binom{N}{r}$ different sets. Let $\mathcal{C}_{r,j}$ be the jth cooperation set with r relays such that $j = 1, 2, \ldots, \binom{N}{r}$, and r denotes the cardinality of the cooperation set, i.e., $r = |\mathcal{C}_{r,j}|$, and $r = 1, \ldots, N$. As an example, $\mathcal{C}_{1,i}$ refers to ith cooperation set with 1 relay, and $\mathcal{C}_{1,1} = \{R_1\}$, $\mathcal{C}_{1,2} = \{R_2\}, \ldots, \mathcal{C}_{1,N} = \{R_N\}$, and likewise $\mathcal{C}_{2,1} = \{R_1, R_2\}$, $\mathcal{C}_{2,2} = \{R_1, R_3\}, \ldots, \mathcal{C}_{2,\binom{N}{2}} = \{R_{N-1}, R_N\}$,

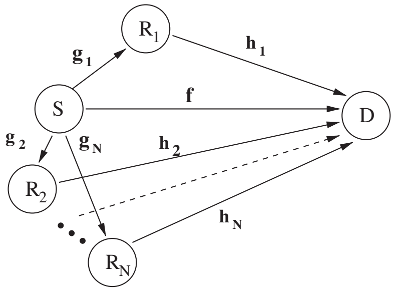

Fig. 1. System model.

and $\mathcal{C}_{N,1} = \{R_1, R_2, \ldots, R_N\}$. Note that, r is an unknown, which we aim to find optimally in this paper. In addition, in our solution, those cooperators are selected optimally among the neighbor nodes, which have successfully decoded the source signal.

Considering the cooperation sets with r relays, the possible cooperation sets can be listed as: $C_{r,\,0}, C_{r,\,1}, \ldots, C_{r,\binom{N}{r}}$, where $C_{r,\,j}$ is the jth cooperation set. Assuming cooperation is performed with set $C_{r,\,j}$, first the source node, S transmits a frame with an energy-per-bit level of E_b Joules/bit, which is phase 1. In phase 2, the nodes in $C_{r,\,j}$, cooperatively transmit the decoded-and-regenerated frame together with S to the destination over orthogonal channels. Here, each cooperator R_i in the cooperator set adjusts its transmission energy-per-bit to a level equal to $\rho_{r,\,j}(i)E_b$ J/b, where $\rho_{r,\,j}(i)$ denotes the relay's relative power level with respect to S's power level, such that $0 \leq \rho_{r,\,j}(i) \leq 1$, $R_i \in C_{r,\,j}$. The power vector, ρ_j involves the relative power level of the corresponding relay node in the cooperation set.

For the wireless channel, independent Rayleigh fading is assumed for all channels. Given the coefficients for source destination (SD), source relay (SR) and relay destination (RD) channels, for instance for relay R_i, are f, g_i, h_i, respectively, the mean channel gains are given as σ^2_f, $\sigma^2_{g_i}$ and $\sigma^2_{h_i}$, respectively. Assuming identical additive white Gaussian noise on all channels with power spectral density of N_o, the instantaneous signal-to-noise ratios (SNRs) for SD, SR and RD channels are found as, $\gamma_f = |f^2|E_b/N_0$, $\gamma_{g_i} = |g_i{}^2|E_b/N_0$, and $\gamma_{h_i} = |h_i{}^2|\rho_{r,\,j}(i)E_b/N_0$, respectively. For the same channels, the average statistics are given as, $\bar{\gamma}_f = \sigma^2_{f_i}E_b/N_0$, $\bar{\gamma}_{g_i} = \sigma^2_{g_i}E_b/N_0$, and $\bar{\gamma}_{h_i} = \sigma^2_{h_i}\rho_{r,\,j}(i)E_b/N_0$.

Due to quasi static fading of low mobility WSNs considered in this work, it can be safely assumed that the channel coherence time is long enough, so that the channel coefficients, mean channel gains and resulting average BER, remain unchanged for several frames within a frame exchange sequence. Assuming BPSK modulation, the average BER of the cooperative system has been derived as [42]:

$$\bar{P}_b(\mathcal{C}_{r,j}, \boldsymbol{\rho}_{r,j}) = \bar{P}_b(\bar{\gamma}_\Sigma)Q(\mathcal{C}_{r,j}) + \bar{P}_b(\bar{\gamma}_f)Q'(\mathcal{C}_{r,j}), \tag{1}$$

where $\bar{P}_b(\bar{\gamma}_\Sigma)$ is the average BER of cooperative transmission, which is an r+1 MISO system, with BPSK modulation subject to Rayleigh fading. For the calculation of this BER value, the following approximation is obtained in [42][1]:

$$\bar{P}_b(\bar{\gamma}_\Sigma) \approx \left[\frac{1}{\pi}\int_0^{\pi/2} \frac{(\sin\phi)^{2(r+1)}}{\sin^2\phi + \bar{\gamma}_f}\, d\phi\right] \prod_{R_i\in\mathcal{C}_{r,j}} \frac{1}{1+\bar{\gamma}_{h_i}}. \tag{2}$$

$\bar{P}_b(\bar{\gamma}_f)$, the average BER of the SD channel is obtained as [43],

$$\bar{P}_b(\bar{\gamma}_f) = \frac{1}{2}\left(1 - \sqrt{\bar{\gamma}_f/(1+\bar{\gamma}_f)}\right), \tag{3}$$

and with γ_{th} given as the average SNR threshold for successful decode-and-regenerate operation, the Q term denotes the probability that all relays in $C(r, j)$ can decode-and-regenerate source's transmission and Q' denotes the complement event, obtained as:

$$Q(C_{r,j}) = \prod_{R_i\in C_{r,j}} e^{-\gamma_{th}/\bar{\gamma}_{g_i}}, \tag{4}$$

$$Q^{'}(C_{r,j}) = 1 - \prod_{R_i\in C_{r,j}} e^{-\gamma_{th}/\bar{\gamma}_{g_i}}. \tag{5}$$

The energy consumption model of the cooperative system considers the energy consumed by source, relay and destination nodes. For the energy cost, we calculate the energy-per-bit cost, which is the amount of energy needed to successfully transmit one bit to the destination. The source node transmits with the maximum available energy-per-bit level, E_b, calculated as $E_b = \epsilon_{t\alpha}d^\alpha$, where $\epsilon_{t\alpha}$ is the energy-per-bit-meter$^\alpha$ at the transmit amplifier and α is the path loss coefficient [44]. Given the average BER target P_{th}, d represents the maximum source-destination separation that allows successful communication. Furthermore, it is assumed that for all nodes, E_t and E_r represent the energy-per-bit spent at transmit and receive circuitries, respectively. Based on these assumptions and findings, the total energy-per-bit cost of cooperative system with relay set $C_{r,\,j}$ and power vector $\rho_{r,\,j}$ is given as:

$$\varepsilon_{r,j}(\rho_{r,j}) = \left(1 + \sum_{R_i\in C_{r,j}} \rho_{r,j}(i)\right)E_b + (r+1)E_t + (2r+1)E_r. \tag{6}$$

The first term in (6) is the energy consumed in the transmit amplifiers of the source and the cooperator nodes, and the second term is the transmit circuitry energy consumption in these nodes. The third term involves the energy consumed at the receiver circuitries, considering receptions at r cooperators during phase 1 and (r+1) receptions at the destination in phase 2. Since only the nodes that can successfully decode the source transmission can participate in cooperation, energy cost due to error propagation is obliterated, and hence it is not considered in (6).

The COMAC framework aims to find the group of relays and actuate them with optimal power levels so as to minimize the total energy consumption[2] while satisfying a

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[1] Average BER approximation is also presented and utilized in the FER calculation in [41].

[2] Note that, here, the energy cost of only the physical layer operations is taken into account. Since potential MAC layer costs are common to all nodes, they are not included in the objective function. However, the MAC layers costs are later included in the energy calculations in the performance analysis.

target average BER, P_{th}, which results in the following optimization problem:

$$argmin_{\mathcal{C}_{r,j},\boldsymbol{\rho}_{r,j}} \mathcal{E}(\boldsymbol{\rho}) \tag{7}$$

$$s.t.\ \bar{P}_b(\mathcal{C}_{r,j}, \boldsymbol{\rho}_{r,j}) \leq P_{th}, \tag{7a}$$

$$0 \leq \rho_{r,j}(i) \leq 1, \quad \forall R_i \in \mathcal{C}_{r,j}, \tag{7b}$$

$$0 \leq r \leq N, \quad \forall \mathcal{C}_{r,j} \subseteq \mathcal{R}. \tag{7c}$$

Note that $\mathcal{E}(\boldsymbol{\rho})$ represents the total energy costs incurred by possible cooperations sets, $C_{r,j}$ with power assignment vector $\boldsymbol{\rho}_{r,j}$, as given in (6). Thus, the objective in (7) is to find the energy minimizing cooperation set and the power levels of the cooperators.

Observing the total energy cost in (6), it can be inferred the transmit and receive circuit energy terms depend merely on the number of relays and the total energy cost of cooperation with r relays can be minimized by optimal assignment of transmit power levels. Hence, the problem in (7) can be solved in two parts as follows. For a given a relay set $\mathcal{C}_{r,j}$, the optimal power vector $\boldsymbol{\rho}^*_{r,j}$ can be obtained by solving,

$$\min \sum_{R_i \in \mathcal{C}_{r,j}} \rho_{r,j}(i) \tag{8}$$

$$s.t.\ \bar{P}_b(\mathcal{C}_{r,j}, \boldsymbol{\rho}_{r,j}) \leq P_{th}, \tag{8a}$$

$$0 \leq \rho_{r,j}(i) \leq 1, \quad \forall R_i \in \mathcal{C}_{r,j}.$$

Next, the optimal cooperation set can be obtained from,

$$argmin_{\mathcal{C}_{r,j}, 0<r\leq N} \mathcal{E}(\boldsymbol{\rho}) \tag{9}$$

$$s.t.\ \bar{P}_b(\mathcal{C}_{r,j}, \boldsymbol{\rho}^*_{r,j}) \leq P_{th}, \tag{9a}$$

$$r = 1, \cdots, N.$$

The optimal relative power assignment vector for a given relay set $\mathcal{C}_{r,j}$ is obtained as the solution for the first problem (8) via the Lagrangian relaxation method in [42] as follows:

$$\rho^*_{r,j} = \frac{1}{\bar{\gamma}_f}\left(\Omega(\mathcal{C}_{r,j}, \bar{\gamma}_f) \prod_{R_k \in \mathcal{C}_{r,j}} \frac{\sigma_f^2}{\sigma_{h_k}^2}\right)^{1/r} - \frac{\sigma_f^2}{\sigma_{h_k}^2 \bar{\gamma}_f}, \tag{10}$$

where

$$\Omega(\mathcal{C}_{r,j}, \bar{\gamma}_f) \triangleq \frac{\Lambda(r, \bar{\gamma}_f) Q(\mathcal{C}_{r,j})}{P_{th} - \bar{P}_b(\bar{\gamma}_f) Q'(\mathcal{C}_{r,j})},$$

$$\Lambda(r, \bar{\gamma}_f) \triangleq \frac{1}{\pi} \int_0^{\pi/2} \frac{(\sin\phi)^{2(r+1)}}{\sin^2\phi + \bar{\gamma}_f} d\phi,$$

with $P_b(\bar{\gamma}_f)$, Q and Q' are calculated via equations from (3) to (5). Note that, here the average BER of the cooperative system is in the constraint of the above optimization problems, and its approximation in (2) facilitates the calculation of the closed form solution for the optimal power vector.

The second part of the problem in (9) evaluates the total cost of all possible relay sets $\mathcal{C}_{r,j}$ with optimal power assignment, and determines the set that satisfies the reliability requirement with minimum energy cost. The resulting solution algorithm from these two joint problems is named as Optimal Cooperator Selection and Power Assignment (O-CSPA). O-CSPA is designed for fast fading systems with reliability constraint in terms of FER in [41], and for slower fading systems with BER constraint in [42]. The distributed implementation, namely, Distributed Cooperator Selection and Power Assignment (D-CSPA) algorithm allows for incremental implementation, where the algorithm starts with the smallest cooperation set with one relay, and increasing the number of relays one by one, all relay sets with optimal power allocation vector are evaluated, until the set that satisfies the BER (or FER) target with minimum energy consumption is found. D-CSPA has been shown to provide similar performance to O-CSPA in various scenarios and settings, as shown in [41] and [42], where the algorithms are evaluated assuming a perfect MAC. This paper's main scope and contribution is the MAC layer design and implementation of D-CSPA, resulting in the COMAC framework for low mobility WSNs with BER requirement.

4. Cooperative MAC framework: COMAC with relay selection and power assignment

The energy optimal distributed cooperator selection and power assignment (D-CSPA) algorithm is implemented in the COMAC protocol in three main stages: (i) Reservation stage, where the medium is reserved and SD, SR and RD channels are estimated, as the cooperative data transmission request is sent by the source node and response received from the destination node, (ii) Available to COoperate (ACO) epoch, where the announcements of the candidate relays are transmitted, additional relay channels are measured, and D-CSPA algorithm is implemented so that the optimal cooperation set is formed with optimal power assignments, and (iii) the cooperative transmission stage, where the source and the selected relays transmit at the assigned power levels to the destination.

Considering a typical cooperative system, as depicted in Fig. 1, with a source and destination and N relay nodes, the COMAC frame exchange sequence is depicted in Fig. 2. In designing COMAC, we propose modifications on IEEE 802.11 MAC protocol [45], so that its reservation and virtual carrier sensing features can be utilized with new packet structures. All COMAC frames, in their headers contain a Duration field that specifies the total time required for the frame to be delivered and acknowledged, and similar to the IEEE 802.11 protocol, the stations listening to the wireless medium obtain the Duration field from each incoming frame and set their Network Allocation Vector (NAV) to this value, specifying how long a station must wait before access. In the COMAC protocol the nodes that do not participate in cooperation defer and they do not access the medium for the NAV duration as depicted in Fig. 2. Calculation of the durations for different packets can be found in [46].

The *reservation stage* starts as the source node sends a Cooperative Request To Send (C-RTS) packet to reserve the medium, similar to RTS of IEEE 802.11; however here the packet type indicates the start of cooperative transmission. Receiving the C-RTS packet, the destination and relay nodes estimate the average SNR values for *SD* and *SR* channels, $\bar{\gamma}_{g_i}$ and $\bar{\gamma}_f$, respectively. If the average SNR of the *SD* channel is lower than the SNR threshold value for satisfying BER QoS, then the destination concludes that cooperation is necessary. Similarly, each relay infers that it is a

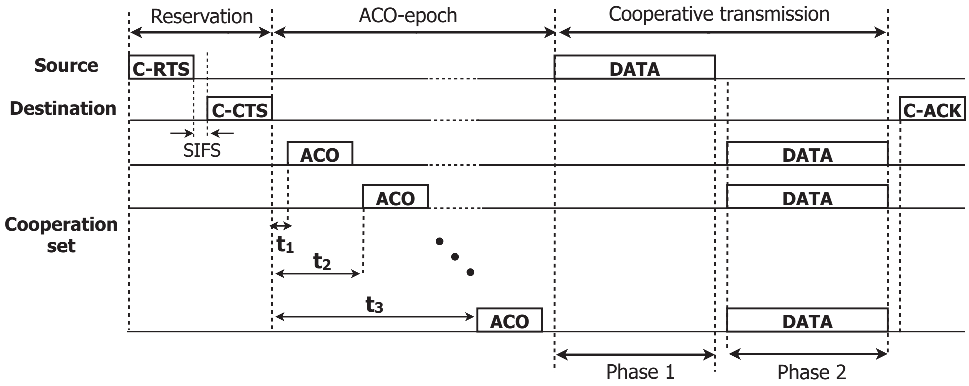

Fig. 2. COMAC frame exchange sequence.

candidate for cooperation if the average SNR estimate for its *SR* link is larger than the SNR threshold. As a response to the C-RTS packet, the destination node sends the Cooperative CTS (C-CTS) packet, which is a modified version of the CTS packet of IEEE 802.11 with an additional field carrying the average SNR value of the *SD* link. Receiving the C-CTS packet, the source node and the relay nodes obtain the average SNR of the *SD* channel (by estimation and reading from the packet, respectively) and determine the necessity of cooperation.

Upon deciding for cooperation, the source node starts the timer for the *ACO epoch*, where each candidate relay node starts an individual timer, which is a multiple of an ACO slot (calculation of slot duration can be found in [46]) for sending an ACO packet, which is a newly defined control packet including the list of nodes in the most recent cooperation set, the current optimal power vector, the average SNR of the *SD*, *SR* and *RD* links. The individual ACO timers for the candidate relays help not only to prevent collisions of the ACO packets, but also to arbitrate and prioritize the relays for implementing the D-CSPA algorithm. Upon receiving an ACO packet, a candidate relay can be in two states: (1) It has already sent an ACO, so with the new ACO, this node just updates the cooperation set and obtains its new power assignment, and (2) If the relay has not sent its ACO packet yet (which means its ACO timer has not expired yet), then it reconsiders its cooperation decision as follows: If the existing cooperation set does not satisfy the BER requirement, then this new relay joins cooperation without checking the energy costs. If the existing cooperation set already satisfies the BER requirement, then this relay checks whether it can decrease the energy-per-bit cost of the cooperative system. If so, then relay decides to join cooperation; otherwise, then this relay cancels its ACO timer and goes to idle state. Having decided to join cooperation, the relay adds itself to the cooperation set, modifies the relative power assignment vector, and starts its ACO timer again for sending its first ACO packet.

At the end of the ACO epoch, if a cooperator set could not be determined due to ACO collisions or the existing cooperation set cannot satisfy the BER requirement, i.e., when the source node decides that the optimal cooperation set is not found, the relay and destination nodes are informed by the source node via an INFO packet, which is a packet introduced within COMAC. In INFO packet, the source node announces whether (i) its call for cooperation is aborted, meaning that the source reverts back to direct transmission, or (ii) it calls for another ACO-epoch. If the source reverts back to direct transmission, relay nodes reset their ACO timers, go to idle state, and the source sends the DATA packet to the destination without cooperation. However, if the source calls for repetition of ACO-epoch, then having received the INFO packet, the relay and destination nodes know that the ACO epoch, say ACO-I, is not successful and another ACO epoch, say ACO-II, will follow, so they update their NAV timers accordingly. Note that although ACO timer mechanism helps avoid ACO collisions, collisions may still occur due to erroneous channel information, or lack of channel state information. Fig. 3 depicts the frame exchange sequence in case the first ACO epoch fails due to collision and a second ACO epoch is initiated by the source node to form a cooperation set. In our proposed scheme, it is assumed that source reverts back to direct transmission at the end of ACO-I only if there has no ACO transmission, i.e., no candidate relay is announced. However, in case of failed ACO-I, it is assumed that the source always calls for ACO-II.

In order to successfully differentiate ACO timers in the second ACO epoch, we propose to use the instantaneous *RD* link power levels, which may be obtained through C-CTS, assuming that channel is symmetric. However, if this channel information is not available, the relay node needs to introduce an extra random back off duration to its previously used timer value. When the ACO-II results in an optimal cooperation set, the source node sends the data packet as phase 1 of cooperative transmission. Otherwise, the source node reverts back to direct transmission, as depicted in Fig. 3. It should be noted that a candidate relay sends at most 2 ACO messages, one in ACO-I, and one in ACO-II, only if cooperation set formation has failed in ACO-I. In case, a feasible cooperation set cannot be found at the end of both ACO epochs, then the source node reverts back to direct transmission.

Let us consider an example scenario to elaborate on the formation of the optimal cooperation set, where *N* neighboring nodes receive C-RTS and C-CTS, successfully, and

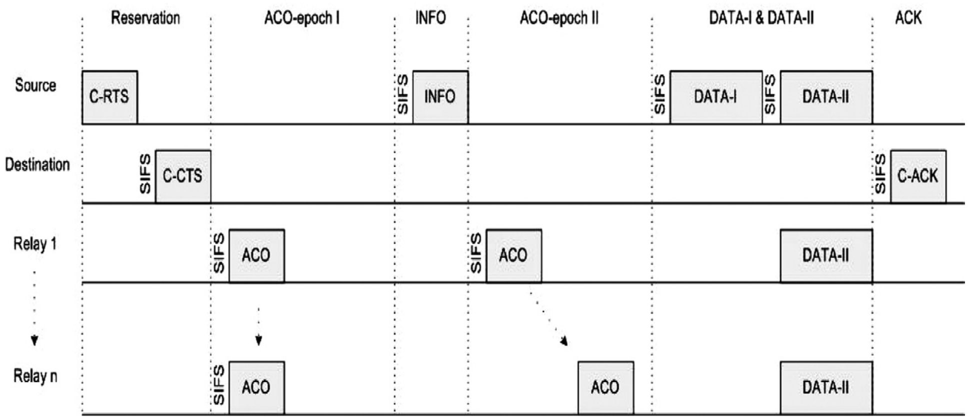

Fig. 3. Frame exchange with ACO collision resolution.

find out that their involvement in cooperation would either help the source node to successfully send its packet to the destination (which would otherwise be unsuccessful due to SD channel condition), or help decrease the total energy-per-bit cost of source-destination communication. Each of these N relays initiates a timer at the expiration of which relay sends an ACO message. The duration of ACO timer is correlated with the energy saving the relay would bring, shorter the duration the better the relay. The details on the ACO timer mechanism are explained in Section 4.1. Let us assume that timer for R_1 expires first, hence relay node R_1 sends its ACO packet. This packet includes the relative power assignment vector $\rho^*_{1,1}$. R_1 also informs other nodes about its channel statistics, i.e., σ_{g_1} and σ_{h_1}. Now, inside the cooperation set there is only one relay, R_1. When other relays hear the ACO message from R_1, they know that R_1 is in the cooperation set, they reconsider their decision, and they recalculate relative power assignment vector based on the information received from R_1. If previous cooperation set is not feasible or if total energy-per-bit cost of the system can be further decreased by participation of R_i into the cooperation, relay R_i favors to cooperate. For example, assuming that the next candidate relay in order is R_2, then its ACO timer will expire next and R_2 will send its ACO packet. Upon receiving the ACO message from R_2, the other relays will know the latest cooperation set, relative power assignment vector and the channel information (σ_{g_1}, σ_{h_1}, σ_{g_2}, σ_{h_2}) of the relays in the current cooperation set R_1, R_2, and each candidate relay applies the same procedure described above in determining whether or not to join the cooperation set. If a relay decides to join cooperation, it sends its ACO packet with the new power assignments. If, after hearing an ACO packet, such as from R_2, a node decides not to cooperate, it cancels its previous ACO timer and goes to idle state. As this procedure is repeated iteratively, the optimal cooperator set is formed incrementally and the search is completed by the end of the ACO epoch.

Having formed the optimal cooperation set and assigned optimal power levels, the source node starts *cooperative transmission* by sending the data packet in phase 1. In phase 2, the source and the nodes in the cooperation set cooperatively transmit the data packet to the destination node over orthogonal channels, such as using Code Division Multiple Access (CDMA) or Time Division Multiple Access (TDMA), at the assigned optimal power levels. When the destination node successfully receives the cooperatively transmitted packet, it sends a Cooperative Acknowledgement (C-ACK) packet. The source node receiving the C-ACK packet infers that cooperative transmission is completed with success. Otherwise, the C-ACK packet is not sent, and the source node initiates a retransmission in cooperation mode.

In summary, each relay makes its own decision in a distributed manner and it sends its decision and calculations via the ACO packet. Also, in the ACO packet D-CSPA algorithm metrics such as channel statistics, current cooperator set and optimal power vector are disseminated among all candidates, so they can recalculate their metrics. Therefore, successful delivery of the ACO packets is crucial for accurate implementation of the D-CSPA algorithm. For one thing, collisions of ACO packets should be prevented. Second, candidate relays should be prioritized, such that they are included earlier in the cooperation set. For this purpose, in the COMAC framework, four types of ACO timers are designed to coordinate the transmissions of the candidate relays, as explained next.

4.1. *ACO timer design*

The design of the ACO timer, which determines the time each ACO message is transmitted, is essential not only for successfully differentiating the ACO packets of the relays from each other, but also for forming the best cooperation set. Here, we propose four timer schemes which differ with respect to the set of channel state and power assignment information utilized for determining the transmit times of the ACO messages.

4.1.1. *Ideal predefined ACO timer values* (τ_1)

In this design, each relay node has a predefined timer value, so that the relays in a cooperation set transmit their ACO packets in the ideal order determined by the channel characteristics of the relays. This timer design results in optimal cooperator selection and leads to most efficient energy consumption, while also completely eliminating the possibility of ACO collisions. However, it is only applicable for cases when the instantaneous and average channel statistics of nodes are precisely known and static, so that the ideal order of relays can be successfully calculated beforehand.

4.1.2. ACO timer based on random slot assignment (τ_2)

This timer does not utilize any information on channel state and power assignment, as opposed to the ideal predefined ACO timer. In this design, each relay node only randomly chooses one of the ACO slots inside the ACO epoch, which may lead to multiple candidate relays to choose the same ACO slot, resulting in collisions. Also, since relay selection is totally random, a relay with large cooperation cost may be selected, instead of a more energy efficient relay. This scheme cannot promise selection of the optimal cooperator set, while preventing ACO collisions to some extent. The strength of this timer is in its simplicity.

4.1.3. ACO timer based on power assignment (τ_3)

The energy-efficiency provided by COMAC depends on the delivery of the ACO packets from the more qualified candidate cooperators before the less qualified ones, since the cooperator set is formed incrementally by adding a new candidate each time an ACO is delivered. In this design, the ACO timer is used for optimally arranging the order of candidate relays to participate in cooperation, so that (1) the resulting relay order should favor the minimal total energy consumption of the cooperative system, and (2) the ACO timer should minimize ACO collisions. Our main motivation is to reduce the total energy consumption of the cooperative system, which is defined in (6). Since the total energy consumption of cooperative system is proportional to the relative power assignment vector of relay nodes. In this timer, we propose to utilize the relative power assignment values of the relays, $\rho_{1,1}(i)$, as the metric to build an effective ACO timer.

The relay nodes can calculate their timers after receiving the C-CTS packet, as the power assignments are calculated for each relay (as if it is the only relay in the cooperation set). Hence, each relay determines its ACO timer based on its average channel conditions only. Calculation of the ACO timer value for relay node R_i can be generalized as:

$$t_i = \beta \rho_{1,1}^{\kappa}(i) \tag{11}$$

Here, the parameters β and κ help to adjust timer to support optimal timer functionality for all scenarios. Relays with low $\rho_{1,1}$ values are expected to be more energy efficient, so they should transmit their ACO packets earlier. Therefore, the timer value should be decreasing as $\rho_{1,1}$ decreases, which can be provided by selecting positive values for the exponent κ. Second, the collisions should be minimized. Note that ACO packet collisions are observed when the minimum difference between ACO timers of relays is larger than the maximum propagation delay in the network. By considering node distributions over different topologies (horizontal, vertical and square grid), optimal power assignments and ACO timers are computed considering different values of (β, κ), and the probability of collisions for each (β, κ) is obtained. After extensive simulation experiments in [46], the parameter values that minimize ACO collision probability have been selected as $\beta = 1/4$ and $\kappa = 1/4$.

4.1.4. ACO timer based on power assignment and instantaneous channel power (τ_4)

The previous timer favors the relays with lower relative power assignment values to join the cooperation set earlier than others. This model works fine for selecting optimal relays. However, when candidate relays are located at symmetrical positions with respect to both source and destination nodes, which could happen in a grid topology, such relays' ACO timer values can be similar. Since the average channel statistics of those nodes would also be similar, ACO collisions can be observed. As a remedy for this problem, τ_3 is modified, so that the instantaneous power level measured over the *RD* link, P_{RD}, is also considered in addition to the relative power assignments. Due to independent fading across different nodes, the instantaneous power of the signal received over the *RD* link will be different for different relay nodes even when they are symmetrically located, and the collisions will be prevented.

In the new metric, the *RD* channel power is normalized with respect to the *SD* channel power, P_{SD}, added to τ_3. The parameters of this additional term are again selected for minimizing ACO collisions, after extensive simulations considering various topologies [46]. The resulting ACO timer for relay R_i is calculated as:

$$t_i = 0.25(\rho_{1,1}(i))^{1/4} + 0.2\left(\frac{P_{SD}(i)}{P_{RD}}\right)^{1/4}. \tag{12}$$

4.2. Cooperative sleep feature

The COMAC framework by nature, minimizes the energy cost of cooperative transmission mainly by employing D-CSPA. Considering the protocol operation, COMAC reduces energy costs by avoiding data collisions with the reservation stage and virtual carrier sensing. Furthermore, the intelligent ACO timers minimize ACO collisions by coordinating the transmissions of the candidate relays. Additionally the ACO collision resolution feature quickly takes care of ACO collisions, helping to form the optimal cooperative set and to enable cooperation. However, idle listening in the protocol can still consume a significant amount of energy, since all nodes stay in idle state in order to receive possible incoming packets [47].

We propose that the relay nodes that will not cooperate, to go to sleep and to wake up only after the cooperative transmissions. Specifically, each node makes its decision to go to sleep after three instances: upon receiving a C-CTS packet, upon receiving an ACO packet and at the end of the ACO epoch upon receiving the INFO packet.

Upon receiving the C-CTS packet, a relay node learns about the transmission mode, whether it is direct or cooperative. In case of direct transmission, the relay can go to sleep until the end of the direct transmission. In case of cooperative transmission, after the C-CTS, if a relay infers

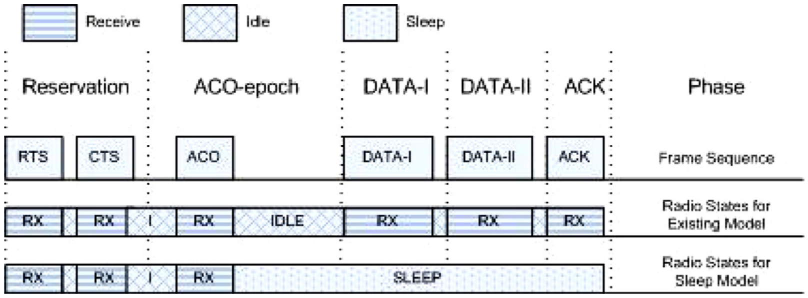

Fig. 4. Radio states with sleep feature.

that it will not participate in the cooperation, it will go to sleep until the end of the ACO epoch.

The relays that are potential candidates after C-CTS, set their ACO timers, and wait for their turn in the ACO epoch, while observing transmitted ACO packets by other candidates. Upon receiving an ACO packet, if a candidate relay decides that it should not be included in the (best) cooperator set, it sets its NAV timer until the end of the ACO epoch and goes to sleep. Otherwise, it remains in idle state to update its calculations for D-CSPA and later takes part in cooperation.

When the NAV timer expires at the end of the ACO epoch, a new NAV/sleep timer will be set depending on the packet sent by the source node: If a data packet is transmitted by the source node, then this is phase 1 of cooperative transmission, and the relay is not included in the final cooperator set, its NAV/sleep timer is set until the end of C-ACK of cooperative transmission. If the source node sends an INFO packet indicating that it is reverting to direct transmission, NAV/sleep timer is set until the end of the ACK of direct transmission. If the INFO packet indicates a second ACO epoch for collision resolution, if the relay is not a candidate, again its NAV/sleep timer is set until the end of the ACO epoch and it is to be re-considered similarly after it expires. Clearly, the relay nodes that are selected in the final cooperator set do not go to sleep.

The setting of the NAV timer upon reception of different packets is shown in Fig. 2. Note that, the additional inter frame spacings and propagation delays are included for each NAV timer. Fig. 4 illustrates the radio states for a relay node that does not participate in cooperation and how it goes to sleep. In this scenario, the relay node receives C-RTS and C-CTS, and it is a candidate relay that decides not to cooperate upon receiving an ACO packet from another relay node.

5. Performance evaluation

The performance of the COMAC framework with distributed cooperator selection and power assignment (D-CSPA) is evaluated via extensive simulations, in comparison to standard non-cooperative Zigbee WSN technology based on IEEE 802.15.4 [4], by observing throughput, delay and energy performance along with overhead costs. The simulations are carried out using ns-2, where the COMAC framework is modeled with the COMAC protocol implemented as the MAC layer, and for physical layer IEEE 802.15.4 air interface is modeled with cooperation at the packet level. For the Zigbee WSN, IEEE 802.15.4 physical layer with direct (non-cooperative) transmission and IEEE 802.15.4 MAC is modeled with RTS/CTS feature, so that the compared cooperative and non-cooperative schemes are both based on CSMA/CA with reservations.

For the wireless channel, we implemented the two-ray ground path loss model with α=4, and all channels, SD, SR_i and R_iD $\forall i$, are assumed to undergo independent Rayleigh fading with average power levels, σ_f^2, $\sigma_{g_i}^2$ and $\sigma_{h_i}^2$ that are determined based on node separations. The values for E_b, E_t, E_r, N_0 and maximum SD separation for direct communication are chosen in accordance with [48] and maximum transmission power is set to 1 mW. At each receiver, the decode-and-regenerate threshold, γ_{th}, is set to 20 dB above the receive (sensitivity) threshold given in [48], above which a packet is considered to be received successfully. The cooperation model at the receiver assumes orthogonal channels with maximal ratio combining, which enhances the received SNR level by the diversity gain.

In the simulations, we consider square grid, horizontal and vertical topologies, as shown in Fig. 5, and a random topology. Note that vertical and horizontal node deployments can be encountered in pipeline or border surveillance applications, where nodes are communicating with another node on the path to the base station; whereas square grid node deployments are typical for habitat monitoring applications, and random node deployments can be encountered in surveillance applications in hostile environments, where nodes are dispersed randomly in the region of interest [49].

In the simulations, a source node generates packets to a destination node according to a Poisson process with a rate of 125 kbps, such that the source node always has a packet in its buffer to send to the destination node. In each case, we consider 10 nodes, which are all in the coverage range of each other, i.e., all nodes can be reached over a single hop through a direct or cooperative link. The size of data packets is 128 bytes, and maximum data transmission rate is 250 kbps in accordance with [4]. The size of the control packets is set as 16 bytes for C-RTS and ACO, 14 bytes for C-CTS and ACK packets, which are large enough to carry the channel state information and power vectors for the implementation of D-CSPA. The control packets, C-RTS, C-CTS, ACO, ACK and C-ACK are assumed to be delivered reliably (except for ACO collisions), so as to clearly

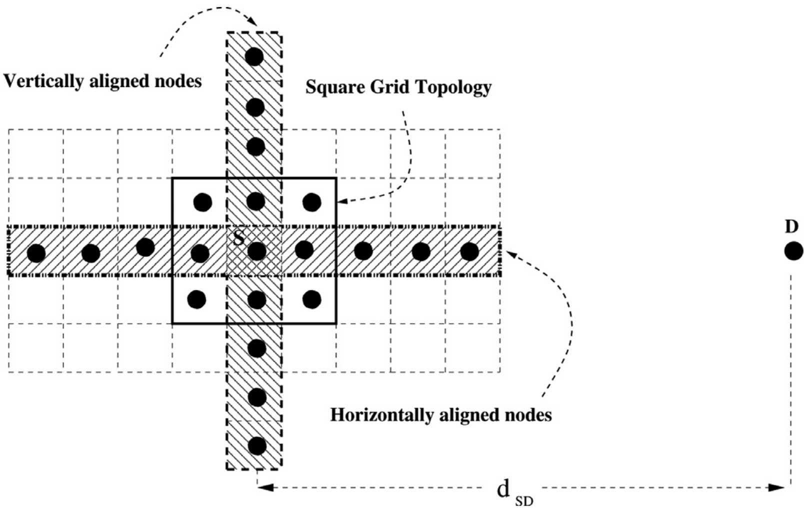

Fig. 5. Nodes deployed in grid topology.

Table 1
Simulation parameters.

Max. data rate	250 kbps	BER thrd.	10^{-4}
C-RTS, ACO, INFO	16 B	Rx sens.	−95 dBm
C-CTS, ACK	14 B	Carrier sens. thd.	−75 dBm
SlotTime	320 μ s	Packet size	128 B
SIFS	192 μ s	Tx Power	1 mW

observe the impact and improvements of cooperation on data transmission. The reliability QoS, target BER in the experiments is set as $P_{th} = 10^{-4}$, and each experiment spans simulation duration of 50 s. The simulation parameters are summarized in Table 1.

5.1. COMAC with D-CSPA

In the first set of experiments, we investigate the performance of the COMAC framework with distributed cooperator selection and power assignment by evaluating the system in terms of energy costs, throughput, delay and overhead. We start with the energy performance of COMAC with D-CSPA in comparison to COMAC with random cooperator selection (denoted as R-CS) and COMAC with only optimal cooperator selection (denoted as O-CS), as well as the direct transmission over Zigbee WSN. Despite implementing cooperation via COMAC, R-CS and O-CS schemes do not perform optimal power assignment, and all nodes transmit at the maximum power level. The goal of this experiment is to demonstrate the effect of relay selection and power assignment in an idealistic setting, where ACO transmissions are collision free and the ACO timers are set as predefined ideal values (τ_1). Fig. 6 depicts the energy-per-bit cost of COMAC schemes obtained as a function of the average SNR of the *SD* channel in the square grid topology. Here, the total energy is calculated by considering all packets (control and data), transmission power levels, transmit and receive energies as well as the number of all involved nodes, and then this total is divided to the number of successfully received bits at the destination, to obtain energy-per-bit cost. As the quality of the *SD* link improves, lower number of relays are needed, hence energy levels decrease with a stair case shape, and the energy savings due to optimal relay selection (D-CSPA and O-CS) can be observed during the transitions of the stair case, where R-CS requires larger number of relays. The results clearly show that the COMAC framework with D-CSPA requires the lowest energy, followed by O-CS. The performance improvement obtained by D-CSPA is especially evident at points where addition of a relay to the cooperation set is inevitable to satisfy the BER requirement. At those points, D-CSPA causes recalculation of power assignment among the cooperation set, such that per-node transmit power level is significantly reduced owing to the added relay. However, O-CS does not employ power assignment, and due this fact, whenever a new relay is inevitably

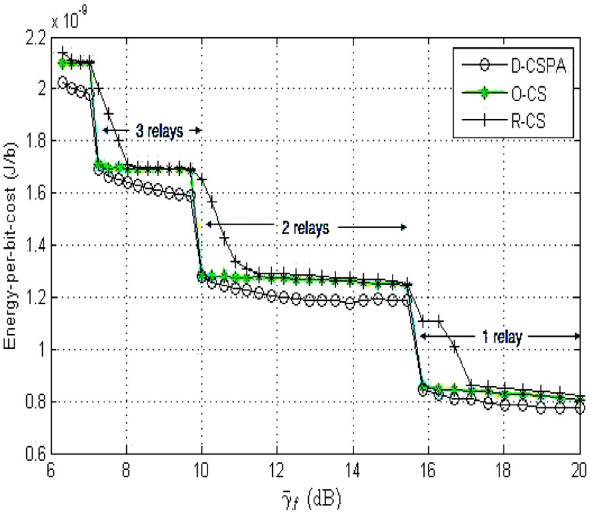

Fig. 6. Energy-per-bit-cost of COMAC with D-CSPA in square grid topology.

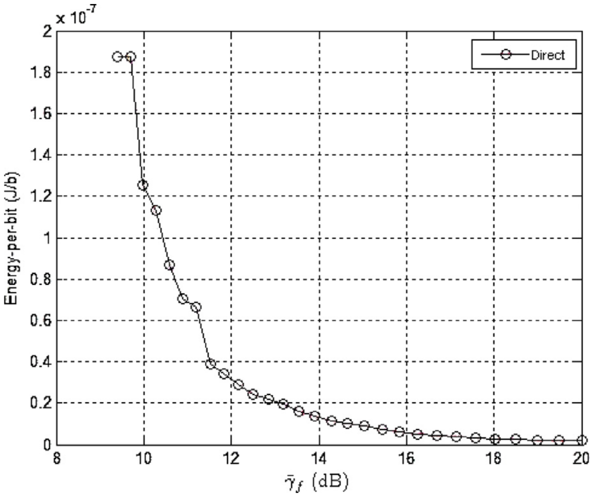

Fig. 7. Energy-per-bit-cost of direct Zigbee in square grid topology.

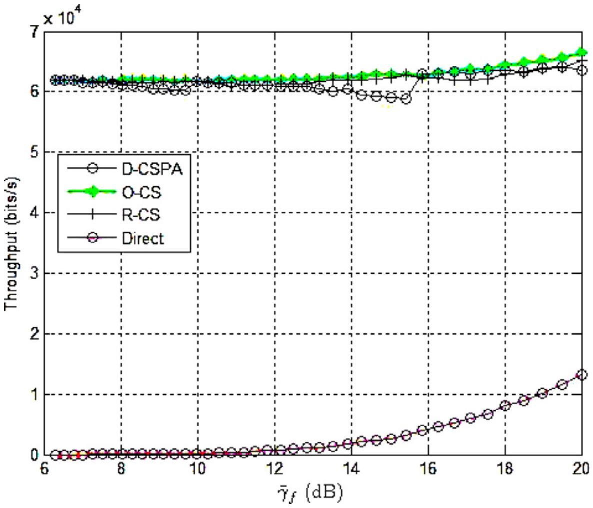

Fig. 8. Throughput of COMAC and direct Zigbee in square grid topology.

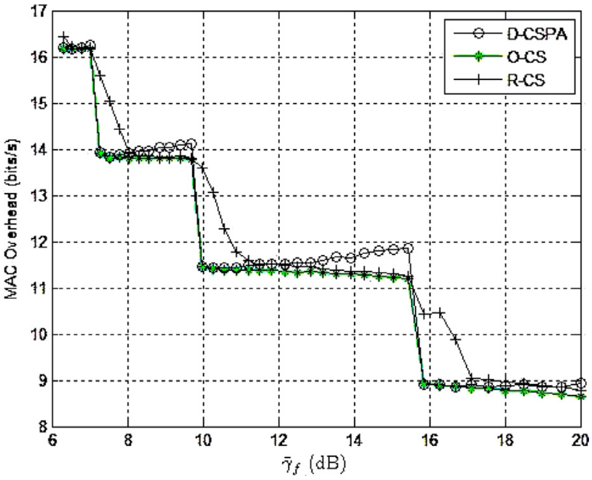

Fig. 9. MAC Overhead of COMAC with D-CSPA in square grid topology.

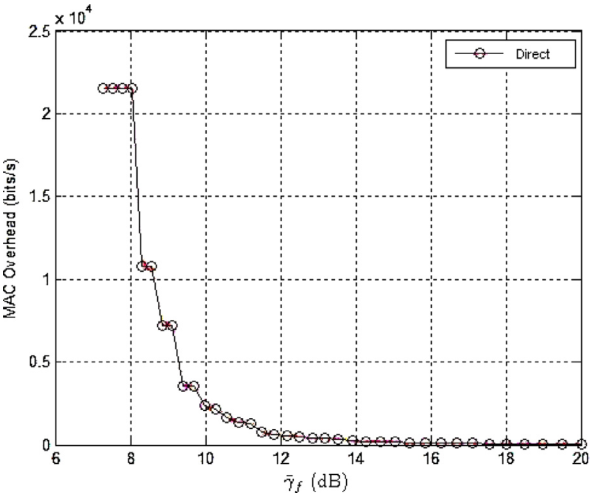

Fig. 10. MAC Overhead of direct Zigbee in square grid topology.

required for the cooperation set to satisfy the BER requirement, total energy consumption is significantly increased. For the same scenario, the energy-per-bit of the standard Zigbee WSN with direct transmission is depicted in Fig. 7, where the energy cost is 2–100 times higher than COMAC. The energy savings of COMAC is due to improved channel quality by cooperation, which results in reduced number of retransmissions and minimization of the energy costs with optimal cooperator selection and power allocation provided by D-CSPA.

In Fig. 8, the throughput performance of the COMAC framework is depicted considering the COMAC framework with D-CSPA, R-CS and O-CS schemes and direct transmission over Zigbee technology for square grid topology. As depicted in these results, all cooperative schemes provide similar throughput, since all of them are designed to satisfy the reliability BER target, which is the constraint of the optimization problem. On the other hand, standard Zigbee WSN with direct transmission can provide only one fifth of COMAC's throughput, only at high SNR. Throughput of Zigbee WSN drops quickly to values close to zero as the *SD* separation is increased.

We have evaluated the MAC overhead, which takes into account the bandwidth consumed by all control packets in COMAC and direct Zigbee schemes. As depicted by the results in Fig. 9 among the cooperative schemes, COMAC with D-CSPA has the highest control packet overhead due to the extra fields used for carrying channel state information in the control messages. However, this cost is still three orders of magnitude lower than the MAC overhead of direct Zigbee technology as shown in Fig. 10 for low SNR. As the SNR is improved, overhead of COMAC schemes drop due to lower number of cooperators involved and the overhead of cooperative and direct schemes are similar. In all cases, the ratio of the MAC overhead to throughput is significantly lower for the COMAC schemes, due to improved throughput.

Next, we present the performance of COMAC with D-CSPA and direct Zigbee WSN in a random topology of

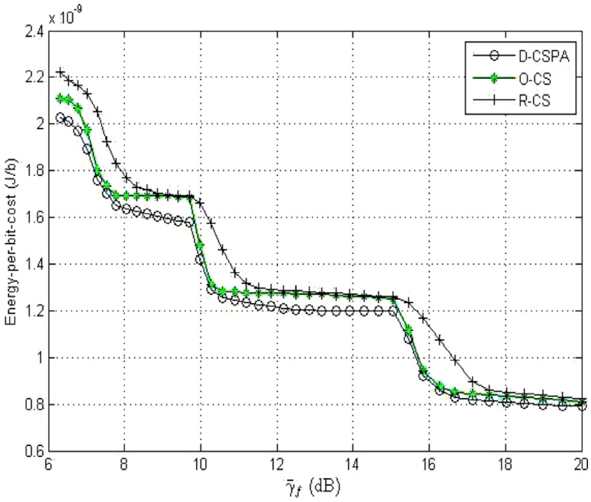

Fig. 11. Energy-per-bit-cost of COMAC with D-CSPA for random topology.

10 nodes, where the results are obtained by averaging the results of 20 network realizations for both cases. Fig. 11 depicts the energy cost of COMAC schemes, and Table 2 provides the comparison of COMAC with D-CSPA and direct Zigbee WSN. It can be observed that the amount of energy savings of COMAC in the random topology is in the same order with the savings observed in square grid topology, resulting in COMAC's cost as 1/94—1/2 of the energy cost of direct transmission.

Table 3 summarizes the throughput and delay performances of COMAC with D-CSPA and direct Zigbee WSN in the random topology. It is observed that the throughput of COMAC with D-CSPA is 4—300 times that of direct transmission, while the delay of direct Zigbee 8—800 times higher than that of COMAC with D-CSPA. Energy, throughput, delay and MAC overhead performance for other additional topologies, such as horizontal and vertical topologies can be found in [46]. In all experiments, we have observed that COMAC with D-CSPA not only offers significant energy savings, but also provides significant throughput improvement and delay reduction with minimal overhead, regardless of the topology and COMAC's performance improvements are similar in all topologies. Note that, especially for low *SD* SNR, direct Zigbee's delay performance is unacceptable for WSNs for IoT [3], whereas COMAC lends itself as a suitable candidate for delay intolerant IoT applications.

5.2. ACO timers and ACO collision resolution

In this section, we investigate the different ACO timer designs. Here, we consider only the vertical topology, because it is the *most challenging* topology in terms of ACO collisions due to its symmetrically located relay nodes. Fig. 12 depicts the throughput results of COMAC with D-CSPA using ACO timers implemented according to: predefined values (τ_1), random slots (τ_2), timers based on power assignment (τ_3), and timers based on power assignment and channel power (τ_4). As shown in the figure, τ_1 provides the highest throughput due to predefined, non overlapping timer values, yielding no ACO collisions at all. τ_3 shows the poorest performance, since ACO timers are adjusted according to power assignments, which are similar in the vertical topology due to symmetric relay locations, resulting in repeated ACO collisions that end up in direct transmission. Here, ACO collision resolution is not implemented to point out the significance of the timer

Table 3
Throughput and delay for the random topology.

$\bar{\gamma}_f$ (dB)	Throughput (b/s)		Average delay (s)	
	Direct Zigbee	COMAC w/ D-CSPA	Direct Zigbee	COMAC w/ D-CSPA
6	~ 0[b]	61658	∞	0.0044
8	~ 0	61385	∞	0.0046
10	185	61140	3.99	0.0045
12	730	60700	1.01	0.0046
14	1800	59250	0.38	0.0047
16	4300	61483	0.15	0.0044
18	8047	62199	0.065	0.0043
20	13106	62159	0.031	0.0042

[b] Significantly low value.

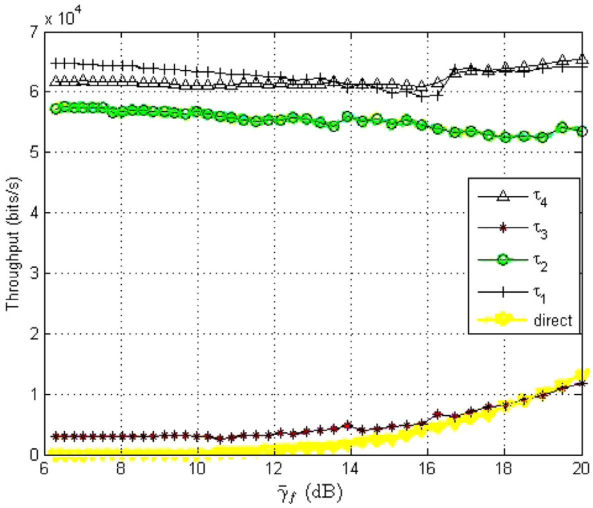

Fig. 12. Throughput performance for COMAC with D-CSPA employing different ACO timers.

Table 2
Energy cost (nJ/b).

$\bar{\gamma}_f$ (dB)	6	8	10	12	14	16	18	20
Direct Zigbee	∞[a]	∞	124	31	12	5.40	2.88	1.80
COMAC w/ D-CSPA	2.03	1.64	1.31	1.21	1.20	0.88	0.81	0.79

[a] Significantly high value.

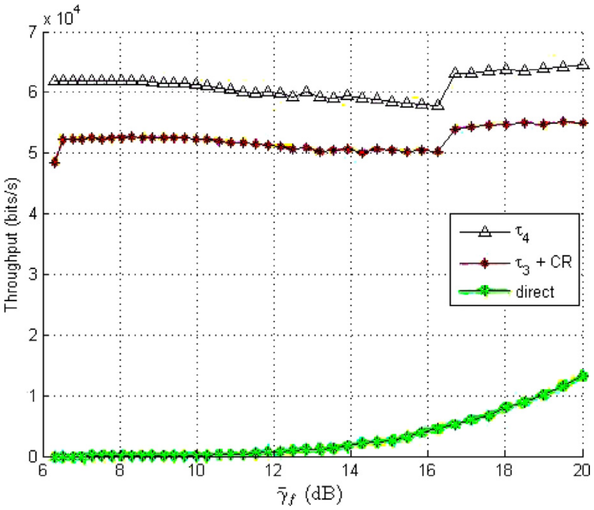

Fig. 13. Throughput performance of COMAC with ACO timer, τ_4, τ_3 with collision resolution (CR) and direct Zigbee.

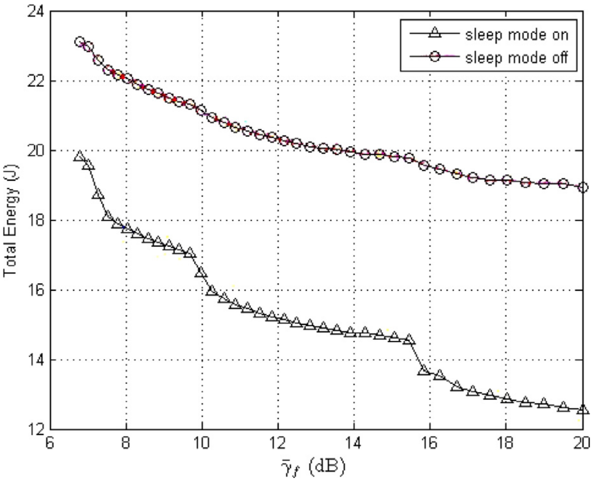

Fig. 14. Total energy consumption of COMAC with D-CSPA and cooperative sleep.

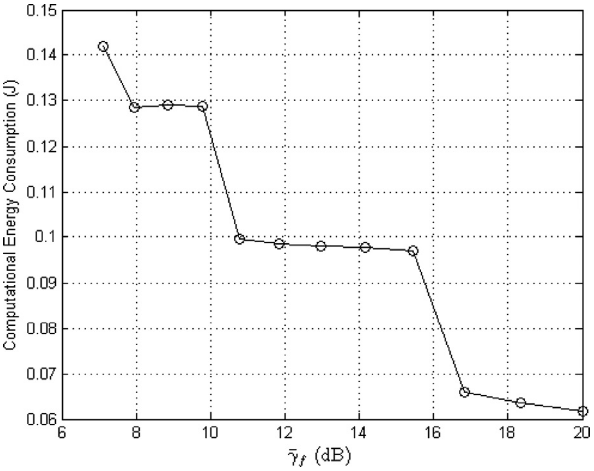

Fig. 15. Computational energy consumption of COMAC with D-CSPA.

choice. The ACO timer τ_4, which makes use of the optimal power levels together with *RD* channel information resolves this issue by differentiating the nodes via the instantaneous power level of the *RD* channels and performs only slightly below τ_1. In [46], the horizontal and square grid topologies are also evaluated, showing that τ_3 and τ_4 perform similarly, slightly below τ_1, since the locations of relay nodes do not challenging, and the random ACO timer, τ_2 exhibits the poorest performance, due to random timers that lead to collisions and poor selection of relays.

Then we incorporate the effect of ACO collision resolution, again considering this *worst case* ACO collision scenario of vertically deployed nodes. In Fig. 13, the throughput performance for τ_3 with proposed ACO collision resolution scheme is plotted together with the performance of the best timer scheme, τ_4. It can be seen that the ACO collision resolution algorithm successfully resolves ACO collisions as the performance approaches the performance of τ_4, and the discrepancy is due to the additional overhead from the second ACO epoch. Note that, the performance of COMAC framework using all timers is significantly above the performance of direct transmission, and the extent of the improvement depends on the timer design.

5.3. Cooperative sleep and computational energy

Finally, the cooperative sleep feature is evaluated by calculating the total energy of the COMAC framework as a function of average SNR of *SD* channel in the square grid topology. Here, COMAC implements D-CSPA algorithm with the best timer, τ_4. In calculating the total energy, in addition to the transmit and receive costs, energy spent during idle and sleep states are also taken into account using the values specified in [48]. Fig. 14 depicts the total energy consumption of COMAC with and without sleep mode. The figure indicates that, as the number of cooperators is increased (which corresponds to small SNR values), energy saving due to sleep mode is decreased. Specifically, energy saving of the system is almost 33% for one cooperator, 25% for two cooperators and 20% for three cooperators.

In the same topology, we have investigated the energy cost of implementing D-CSPA within COMAC by considering the cost of computations through the total cost of arithmetic operations and comparisons. Assuming a 16-bit 1 MHz micro controller and each instruction is completed in one clock cycle, the instruction cost is 594 pJ [50]. The total computational energy consumption of the system is calculated by considering the total number of instructions when COMAC with D-CSPA with the sleep feature enabled per node and also considering the cost of all involved nodes. The results, shown in Fig. 15, indicate that the computational energy cost is very small, ranging between 0.5 and 0.76% of the total energy consumption without cooperative sleep, depending on number of relay nodes included in the cooperation set. When cooperative sleep is enabled, ratio of computational energy to total energy is slightly higher, but still negligibly low.

Performance analysis presented in this section consider one level of reliability QoS, i.e. one target BER level, in a scenario with a single source-destination pair assuming ideal orthogonal cooperative transmissions, in order to prevail the improvements brought by cooperation to state of the art WSNs via the COMAC framework with D-CSPA. The reader can be referred to [42], for the performance study of O-CSPA and D-CSPA with respect to different BER target levels, and to [46] for the performance of COMAC with D-CSPA in a scenario with multiple source-destination pairs, as well as considering TDMA and CDMA schemes for the cooperative transmission stage. These experiments and results complement the analysis presented here, but they are not included in this manuscript for brevity.

6. Conclusions

COMAC is proposed as a cooperative MAC framework that implements distributed cooperator selection and power assignment (D-CSPA) algorithm for minimizing the energy costs of low mobility WSNs, while achieving reliability in terms of BER. In this framework, the relay nodes announce their cooperation decisions via ACO packets, which are coordinated by the ACO timer for the incremental implementation of D-CSPA. Four different ACO timers are designed for different cases, where different amount of channel state information and complexity are considered.

It is shown through extensive simulations that when the average channel statistics and instantaneous channel state information are available at each relay node, the performance of the ACO timer (τ_4) turns out to be very close to the ideal timer (τ_1), providing at least two orders of magnitude improvement in the energy costs, at least a factor of five in throughput, and up to three orders of magnitude in delay, as compared to the standard Zigbee WSNs with direct transmission. The MAC overhead cost of COMAC is similar if not significantly smaller than the overhead of direct Zigbee, depending on the channel quality. Addition of a second ACO epoch and ACO collision resolution enhances the protocol performance when deployed challenging topologies. Despite slightly lower throughput and increased MAC overhead as compared to the ideal COMAC with sophisticated timers (τ_1, τ_4), COMAC with a simpler timer (τ_3) along with ACO collision resolution outperforms direct transmission in all aspects. With the cooperative sleep mode for the relay nodes, additional energy savings of up to 33% is possible while the throughput of the cooperative system remains unchanged. All these performance gains are achieved with almost no additional energy cost for computations, as computational energy is only 0.5% of the total energy cost.

In summary, the COMAC framework is a strong candidate for improving the state of the art of Zigbee WSNs for IoT. COMAC brings about significant performance improvements with very simple changes in the MAC layer to enable optimal cooperation in the physical layer.

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M. Sarper Gokturk received his B.S. degree in Electrical and Electronics Engineering from the Middle East Technical University, Ankara, Turkey in 2004, his M.S. degree in Electrical/Telecommunications Engineering from Drexel University, PA, USA in 2006, and his Ph.D. degree in Electronics Engineering from Sabanci University, Istanbul, Turkey in 2011. Between March and October 2010, he was a visiting researcher at the Integrated Information Systems Laboratory of Polytechnic Institute of New York University, NY, USA. He is currently Research Engineering Team Leader at AirTies Wireless Networks. His research interests are in wireless communications and networks, in particular, media access control, cross layer design and cooperative communication architectures.

Ozgur Gurbuz received her B.S. and M.S. degrees in Electrical and Electronics Engineering at Middle East Technical University, in 1992 and 1995, respectively. She received her Ph.D. in Electrical and Computer Engineering from Georgia Institute of Technology in 2000. From 2000 until 2002, she worked as a researcher/systems engineer for Cisco Systems, Wireless Access and Wireless Networking Business Units. In 2002, she joined the Faculty of Engineering and Natural Sciences at Sabanci University, where she is currently an associate professor. Her research interests lie in the field of wireless networks, specifically, medium access control, radio resource management and cross-layer design.

Murat Erman received his B.S. degree in Electrical and Electronics Engineering from Bogazici University, Istanbul, Turkey in 2001, and his M.S. degree in Telecommunications Engineering from Sabanci University, Istanbul, Turkey in 2003. He is currently Engagement Manager at Ericsson.