Bacterial Foraging-based Power Allocation for Cooperative Wireless Sensor Networks

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Abstract. Cooperative communication becomes a popular area of research due to its strength and wide application scope in wireless networking and communications. This technique improves the communication performance largely in capacity enhancement, energy-efficiency, timeliness and contention. Power allocation plays an important role in the cooperative communication paradigm to get the desired performance improvements in the aforementioned aspects. In this paper, we present a bacterial foraging optimization algorithm (BFOA)-based power allocation method for cooperative communications in wireless systems. Comparative measures with non-cooperative approaches are made to justify our proposed method.

Keywords: Wireless Communications, Bacterial Foraging, Constrained Optimization, cooperative Communication, Signal Combining.

1 Introduction

Cooperative communication attracts much attention in wireless communications due to its potential to increase the received signal strength with multiple packets using reduced transmit power. Increased signal strength in turn provides capacity enhancement, energy efficiency, timeliness and reduction in contention.

For example, if the source node S intends to send data to the destination D, the relay node R also sends the same packet received from the source node S. The destination node D therefore combines both the signals received from the source and the relay in order to boost the signal strength. Here, a single relay or a number of relays in the vicinity can contribute to the relaying activity.

In cooperative communications relay node selection and power allocation have ultimate impact on the performance. The best node or the set of best nodes participating as relay(s) influence(s) the performance as the channel condition varies from link-to-link. On the other hand the tradeoff exists as improving the signal strength by injecting packets increases the contention over the networks.

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In wireless sensor networks (WSNs), distributed approaches dominates the design criteria of all the aspects of networking and selection mechanisms. Considering a homogenous deployment it is not desirable some of the tiny sensors will bear the additional responsibility maintaining and managing the clusters. Centralized environment generally requires explicit messaging for maintenance and therefore undesirable for such homogeneous sensor network deployments.

The **major contributions** of this paper are: (1) Solving the power allocation problem on the cooperative communication paradigm in WSN under constrained receive sensitivity is addressed by utilizing bacterial foraging optimization algorithm (BFOA) in order to minimize the transmit power consumption while achieving the desired received signal strength. (2) The proposed technique provides throughput, energy, timeliness and contention based performance improvements due to the enhancement of the received signal strengths while sending packets with small fraction of transmit power compared to the non-cooperative (NC) communications.

2 Background

Cooperative communications have been increasingly studied in the context of WSN. Reference [16] proposes cooperative communication scheme where sensors in each cluster relay data to the adjacent clusters utilizing the cooperative communication scheme. This technique is only suitable for the cluster based sensor networks. This proposition is not suitable in cases where all the nodes in the network has similar role and no node is superior enough to take additional responsibility to serve as cluster head.

Among the subtopics of the cooperative communications power allocation techniques dominates the interest due to its importance. Reference [14] proposes half transmission power allocation solution (HTPAS) where the transmission power of the relay is set to half of the source's power. Results show the performance is better than the equal power allocation scheme. This simple scheme neglects intelligent allocation of constrained minimization of transmit power.

Equal power allocation (EPA) equally allocate powers to the sender and receiver with a constrained outage probability [5]. The family of simple equal power allocation schemes are almost always inferior to the optimized power allocation scheme while considering the power consumption.

Reference [8] provides a heuristic based approach where the algorithm attempts to minimize the energy cost by utilizing an iterative approach. Reference [11] provides two different heuristic approaches named maximal channel gain (MCG) and least channel correlation (LCC) algorithms under different constrained such as the energy and delay constraints. Hubristic algorithms are rather intuitive approaches. We intentionally avoid designing a hubristic based approach because of the lack of fundamental background behind the algorithms.

Reference [7] solves the power allocation problem in the cooperative communications with decode and forward mechanism where the constraint is defined as the symbol error probability of the radio links. The approximate solution takes a form of water-filling strategy. Unfortunately the water-filling approaches poses the limitation of on convergence in multiple constraints and the improved solution has been proposed [10] for cognitive cooperative communications.

A number of different optimization tools have been utilized in the cooperative communication paradigm. Reference [6] proposes a joint optimization of routing, relay node selection and power allocation under constraint signal to noise ratio by utilizing mixed-integer optimization framework. Reference [4] proposes linear programming approach to solve the multi-source, multi-relay cooperative networks. Reference [15] presents reliable and energy efficient cooperative communication (REEC) technique utilizing simulation annealing based optimization approach to solve the power allocation problem in cooperative communications. Contrarily, we have developed a cooperative power allocation technique for resource constrained WSN based on the BFOA.

3 Proposed Method

This section deals with the underlying theme of the BFOA, the cost function utilized in the BFOA along with the complementary techniques utilized along with our cooperative power allocation scheme. Where the proposed algorithm provides output as Θ:$(P_{Tx}(S)_{dBm}, P_{Tx}(R)_{dBm})$.

3.1 Bacterial Foraging Optimization Algorithm (BFOA)

BFOA is a bio-inspired optimization algorithm similar to ant colony optimization or particle swarm optimization. BFOA is derived from the group foraging behavior of bacteria such as E.coli and M.xanthus. More precisely it is the chemotaxis behavior of bacteria that will perceive chemical gradients in the environment (such as nutrients) and move toward or away from specific signals.

Bacteria decides about the direction of the food based on the gradients of chemicals in the surrounding environment. On the other hand bacteria's secretion attracts and repels each other and control their search direction in the environment. E.coli bacteria uses flagella moves chaotic by tumbling and spinning. It also moves directionally known as swimming. Utilizing (i) chemotaxis (ii) reproduction and (iii) elimination dispersion the bacteria stochastically and collectively swarm toward optima. The detail algorithmic description of BFOA is found in [9].

Mimicking the bacterial behaviour the underlying algorithmic functionalities follow the steps: (a) initializing foraging parameters and variables (b) specifying upper and lower limits of the variables (c) initializing elimination-dispersal, reproduction and chemo-taxis (d) generating bacterial population and positions (e) updating bacteria locations by using tumbling and swimming and (f) executing bacterial reproduction and elimination process.

Let us denote the number of bacteria as S_b, the chemotactic loop limit N_c, the swim loop limit N_s, the reproduction loop limit N_{re}, the number of bacteri for reproduction S_r, the elimination-dispersal loop limit N_{ed}, step-sizes C_i, and the probability of elimination dispersal P_{ed}, respectively.

The chemotactic step is modeled with the generation of a random search direction by $\phi(i) = \Delta(i)/(\sqrt{\Delta(i)^T \Delta(i)})$ also known as tumble, where $\Delta(i)^n$ is the n-dimensional vector with elements having limits of $[-1, 1]$. Each bacterium $\theta^i(j, k, l)$ modifies its position known as swim by $\theta^i(j + 1, k, l) = \theta^i(j, k, l) + C(i)\phi(i)$, where C_i is the step-size for each direction $\phi(i)$.

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BFOA power allocation $\Theta$:$(P_{Tx}(S)_{dBm}, P_{Tx}(R)_{dBm})$
while $(Improvement > Threshold)$ {
    $\Theta = \digamma(\Theta)$ {
        Initialize: $S_b$, $N_c$, $N_s$, $N_{re}$, $S_r$, $N_{ed}$, $C_i$ and $P_{ed}$
        Create initial swarm of bacteria as $\theta^i(j,k,l)\forall i$ where $i = 1 : S_b$
        Find $\tau = f(\theta^i(j,k,l))\forall i$
        for $l = 1 : N_{ed}$ {
            for $k = 1 : N_{re}$ {
                for $j = 1 : N_c$
                    for $i = 1 : S_b$
                        Chemotactic step for bacterium $\theta^i(j,k,l)$ controlled by $N_s$
                Reproduction with probability $S_r$
            }
            Elimination-dispersal with probability $0 \leq P_{ed} \leq 1$
        }
    }
}
$\tau = \aleph(\Theta)$ {
    $p_f = 3.01^i$
    if $(\hat{P}_{Rx}(S) + \hat{P}_{Rx}(R) > P_{Rx}(Th))$ {
        $C_{BB}(\hat{P}_{Tx}(S), \hat{P}_{Tx}(R)) = P_{Rx}(Th) - (\hat{P}_{Rx}(S) + \hat{P}_{Rx}(R))$
        $\aleph = \hat{P}_{Tx}(S) + \hat{P}_{Tx}(R) + |\log(-C_{BB} * p_f)|$
    }
    else
        $\aleph = \infty$
}
```

Fig. 1. BFOA power allocation algorithm.

In each swim the cost is evaluated. If $f(\theta^i(j+1,k,l)) < f(\theta^i(j,k,l))$ the swim is repeated up to N_s times.

The reproduction steps consists of sorting the bacteria population in terms of the objective function. The worse S_r number of the population is destroyed and the best S_r population is duplicated to maintain the population fixed.

In elimination-dispersal step elimination of the bacteria takes place with a probability of P_{ed}, where $0 \leq P_{ed} \leq 1$.

3.2 Cost Function for BFOA

We attempt to utilize the algorithmic strength of BFOA to minimize the energy cost while maintaining the minimum allowable received signal strength utilizing the maximal ratio combining (MRC) scheme of the cooperative sensor networks.

Let, $P_{Tx}(S)$ and $P_{Tx}(R)$ are the powers to be assigned at the transmitters at the source S and relay R. And let $P_{Rx}(Th)$ be the receive sensitivity of the receivers. The designed algorithm therefore assigns Θ:$(P_{Tx}(S)_{dBm}, P_{Tx}(R)_{dBm})$ such that the resultant signal strength by MRC combine at the destination D becomes greater than the receive sensitivity. Alternately the sum of the received signal strengths $P_{Rx}(S)$ and $P_{Rx}(R)$ is greater than $P_{Rx}(Th)$. Let, the $P_{Tx}(min)$ and $P_{Tx}(max)$ are the minimum and maximum allowable level of the transmit power respectively. Then, $P_{Tx}(min) \leq P_{Tx}(S) \leq P_{Tx}(max)$ and $P_{Tx}(min) \leq P_{Tx}(R) \leq P_{Tx}(max)$ becomes the other constrains of the minimization.

$$P_{Tx}(T) = P_{Tx}(S) + P_{Tx}(R) \text{ s.t. } \begin{array}{l} P_{Rx}(S) + P_{Rx}(R) > P_{Rx}(Th) \text{ and} \\ P_{Tx}(Min) < P_{Tx}(S) < P_{Tx}(Max) \text{ and} \\ P_{Tx}(Min) < P_{Tx}(R) < P_{Tx}(Max) \end{array} \tag{1}$$

Penalty Function To achieve to aforementioned constrained optimization we employ BFOA. Note that the core BFOA provides method for the simple optimization. Making it a constrained optimization several techniques may apply such as primal method, penalty method dual and cutting plane method Lagrangian method. The proposed algorithm employ the logarithmic penalty function method while achieving the constrain in the BFOA.

Let $\hat{P}_{Rx}(S)$ and $\hat{P}_{Rx}(R)$ are estimated received power at D from S and from R respectively. Algorithm approximate the resultant receive power. If this evaluated power becomes less than the acceptable threshold then the basic building block of the penalty cost is set to $C_{BB}(\hat{P}_{Tx}(S), \hat{P}_{Tx}(R)) = P_{Rx}(Th) - (\hat{P}_{Rx}(S) + \hat{P}_{Rx}(R))$. Otherwise, the penalty cost is set to ∞. The resultant cost is defined as $\tau = \hat{P}_{Tx}(S) + \hat{P}_{Tx}(R) + |\log(-C_{BB} * p_f)|$. Here p_f is a multiplication factor that depends on the algorithmic round. In our evaluation we define $p_f = 3.01^i$ for the i_{th} round of the algorithmic run. Note that, $\hat{P}_{Rx}()$ can be modeled as $\hat{P}_{Rx} = \Im(P_{Tx}, d, \gamma)$ as per Friis transmission equation.

3.3 Complementary Techniques

The proposed power allocation technique is the bare allocation of power at the sender and the relay nodes. The complementary techniques therefore are the other mechanisms required to complete the other functionalities of the networking; described in the following subsections.

Routing: The sensor network can be of a flat or a cluster based structure. In homogeneous deployment a simple flat architecture is often preferred. In the flat architecture, the well-known distributed routing technique named greedy forwarding attracts much attention in recent days due to its simplicity and usefulness. The distributed geographic location aware greedy forwarding algorithm is the basis of our routing approach [12]. Further specifying, the Euclidian least reaming distance based routing algorithm employed in our evaluation of the sensor networks as [3].

According to this approach, let the node i intends to forward a packet toward the destination. And let N_i defines the set of the neighbor nodes of node i. Node i calculates $\min(d(N_i, \mathcal{C}))$ for the set of N_i and selects the calculated node as the next-hop. Note that $d(j,k)$ defines the Euclidean distance of node j and k.

Access Control: Due to the distributed nature of the WSN architecture, carrier sense multiple access with collision avoidance (CSMA/CA) based simple medium access control (MAC) mechanism is taken as the basis of the access control mechanism. To accommodate the cooperative communications we in fact implemented a modified CSMA/CA in our approach.

Here, each node detecting a busy medium waits for at least twice the transmit time requirement of a single packet before the next attempt to access the medium. Such modification attempts to is to provide priority on relaying packets as the relay nodes priorities cooperatively sending the copy of the packet over its own data packets or the packets it acts as a next hop node to forward. Without such modifications in a simple MAC the same packet occupy unnecessary buffer as multiple copies of same packet remains in multiple nodes over the time.

Relay Selection: Multiple relays can contribute more in the signal boost up with a trade of in the bandwidth inefficiency. In cooperative relay networks n number of relay nodes require $n+1$ different channels. A number of relay selection mechanism therefore introduced in the literature to find the best relay node(s). To achieve such bandwidth advantage we therefore chosen a single relay based cooperative communication scenario in our approach.

In a single relay based approach a number of min-max based relay selection mechanism is devised. Imperfect channel information with min-max algorithm is utilized in our approach while defining the relay node using the method in [13].

According to this approach let a packet is flowing through path consisting of links L_i. For each link L_i there exists a source S and a destination D pair. A potential relay of the link L_i can be of the neighbor nodes in the forwarding path only. Let N_{fi} defines the set of nodes satisfies all the three conditions: (i) N_{fi} are in the radio range of S and D (ii) located closer to the sink compared to the S and finally (ii) closer to the S compared to the D.

Here, the costs of the channels of any pair of nodes ($S \rightarrow N_{fi}$, $N_{fi} \rightarrow D$ and $S \rightarrow D$) are define by the reciprocal to received signal strengths of the pairs. Note that the signal strength can be depicted as a simplified view of the channel condition. Let $C(i,j)$ define the transmission cost from node i and j. The selected relay therefore is the relay satisfies $\max(\min(C(S, N_{fi}), C(N_{fi}, D)))$.

Relaying: The relaying is of amplify and forward approach where a single relay is utilized as an helper node that relay the received packet from the source without any decoding. Upon receiving both the packets from the source and relay the receiver utilize maximal ratio combining (MRC) as signal combining approach to boost the signal strength.

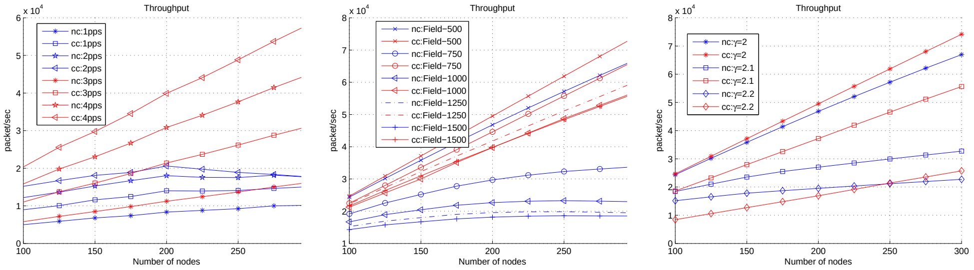
MRC combines the signal in such way that the gain of each channel is made proportional to the root mean square (RMS) signal level and inversely proportional to the mean square noise level in that channel. A detailed performance analysis of single relay amplify forwarding based MRC is in [2], limited to physical layer characterization. Note that this characterization that follows the trend of cooperative communications research where the upper layers are completely ignored. Note that such evaluation is sufficient only for the TDMA like MAC approaches. For the distributed MAC layering approach as CSMA-CA a upper layer consideration is crucial as employed in our evaluation strategies.

4 Experimental Results

We simulate the proposed power allocation technique in Matlab. Where the sensors are deployed randomly and generate packets. Data generated in the field is delivered to the sink in the central location in a multi-hop fashion.

The Chipcon CC2420 dataset [1] values are taken as the transceiver characteristics. Here, the allowable transmit power settings are $P_{dbm} = [0, -1, -3, -5, -7, -10, -15, -25]$. The random backoff as is set to $rand() * 2^{BF-1} * 51.2 * 10^{-6}$ second, where BF denotes the backoff flag. The packets are of 128 byte size. The packet processing time is 2 msec. The retransmission timeout is 3. The physical channel is modelled as Rayleigh fading channel.

A number of N sensors have been deployed in the squared sensor field of length L. During the evaluation the number of the nodes are varied as $N = 100$:



(a) Different packet rates. (b) Different field lengths. (c) Different γ values.

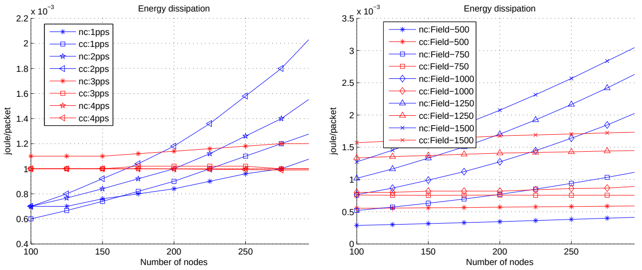
Fig. 2. Throughput performance of the protocols.

50 : 300. Three different aspects of variation in the parameters are considered in this literature: (i) field size and γ remain constant as $L = 1000m$ and $\gamma = 2$ with varying packet generation rate in packet per second (pps) $pps = 1 : 1 : 4$ and (ii) packet generation and γ remain constant as $pps = 4$ and $\gamma = 2$ while the filed length is varied with the length $L = 500m : 250m : 1500m$ and (iii) field size and packet generation rate remain constat as $L = 1000m$ and $pps = 4$ with varying γ with $\gamma = 2 : 0.1 : 2.2$. 200 different random fields are generated in each scenario and averaged out for the results presented. Note that, each deployment assumes a connected network, where each node has at least one neighbor in the forwarding path to send the data to the sink. In case of low density deployments, cooperative communications may not provide sufficient gain in terms of energy efficiency, especially, due to the fact that there may not be a relay node available in the right place. In such scenario no cooperation takes place. Such situation is defined by $d^{\gamma}_{S,D} > d^{\gamma}_{S,R} + d^{\gamma}_{R,D}$.

Figs. 2–5 present performance of the proposed algorithm compared with the NC. The sub-figures (a), (b) and (c) corresponds to the parameter settings of (i), (ii) and (iii) respectively.

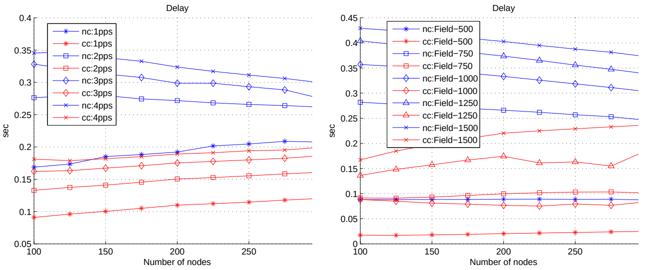
Throughput: Fig. 2 presents the throughput performance of the proposed protocol along with the non-cooperative communication. Fig 2(a) presents the throughput performances of the schemes in different packet generation rates. In all the cases the proposed cooperative communications (CC) outperforms the non-cooperative (NC) counterpart. Note that the increasing number of generating packets does not result increasing the throughput in NC as efficiently as NC. In fact in case of high density deployments with 225 nodes or above and with pps 3 or above the throughput starts to fall due to inefficiency of the NC.

Fig 2(b) presents the throughput performance of the protocols with different field sizes. Increasing the field sizes causes the NC performance decreasing. This is due to the fact that increasing the size in turn increase the hop distance a packet needs to flow from the sender to the sink. As the successful packet reception in each hop is lower than that of CC. The multi-hop cases the rate of reception decays exponentially with the increasing of the hop count. For example, if the reception of each hop in case of C and NC is 90% and 80% respectively. After the second-hop and after the third-hop the C reception becomes 81% and 72.9% respectively where the NC becomes 64% and 51.2% respectively.



(a) Different packet rates. (b) Different field lengths. (c) Different γs.

Fig. 3. Energy performance of the protocols.



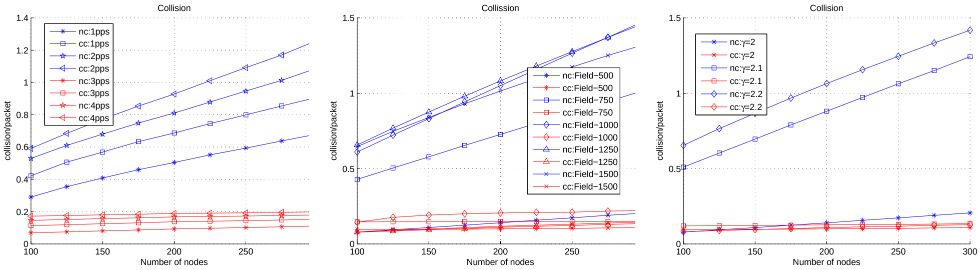
(a) Different packet rates. (b) Different field lengths. (c) Different γ values.

Fig. 4. Delay performance of the protocols.

Fig 2(c) presents the performance of the throughput in different γ. Like the previous cases the CC outperforms the NC. In this aspect there are some exceptions in $\gamma = 2.2$ and with a comparatively less number of nodes in the filed. Note that with low density network there is provision where we do not have available cooperative nodes in a good location.

Energy Dissipation: Fig. 3 presents the energy costs of the CC and NC approaches. Fig. 3(a) shows that increasing of the *pps* increases the energy dissipation of NC abruptly in high density networks. Though the number of packets in the systems are increasing, CC is not affected by implosion of power as much as in case of NC due to its superiority, in terms of capacity improvement. Fig. 3(b) shows the energy dissipation with increased field size. Increasing the filed size causes increasing is energy dissipation in the field due to multi-hop transmissions. But increasing the number of node does not affect the system largely in case of CC. On the other hand the NC not only cannot handle the high data rate but also suffer from high energy dissipation in high density deployment scenarios. Indeed, in some parameter settings the energy performance of the NC outperforms CC (such as in Fig. 3(c)) this is due to the fact that multiple packets (in CC) instead of a single packet (in NC) is transmitted in each link.

Delay: Fig. 4 presents the delay performance of the protocols. Fig. 4(a) shows the delay performance of the communication paradigm with increasing *pps*. The delay increases with increasing of data rates eventually due to higher number



(a) Different packet rates. (b) Different field lengths. (c) Different γ values.

Fig. 5. Collision performance of the protocols.

of collisions. In terms of increasing number of node deployment delay in CC increases due to the same reason i.e., increasing nodes increases the packets in the networks. In case of NC increasing the node results decreasing the delay performance this is due to he far lesser number of packets in sink due to the high packet drops. Note that packets only received at the sink is counted for the delay. Fig. 4(b) shows the performance of delay with increased field size. Eventually increasing the field size increases the delay due to multi-hop functionality. Fig. 4(c) shows the delay performance in different γ. Increasing γ results increasing retransmissions and results increased delay in the networks. In all the cases in Fig. 4(a), Fig. 4(b) and Fig. 4(c) CC outperforms NC due to its signal enhancement and low power transmitter settings.

Collision: Fig. 5 presents the collision performance of the algorithms. The performance measures reveal useful rational behind the improved performance of our proposed CC. Fig. 5(a) reveals that in case of increased node density the proposed CC algorithm does not affected largely due to its low power transmissions. On the other hand with increased *pps* and/or with increased node density NC's collision rate increases abruptly results poor throughput, high energy dissipation (with exceptions) and high delay. In case of varying field size the collision rate jumps in NC due to the shift of single hop to multi-hop presented in Fig. 5(b). Where collision performance of CC remains almost the same. And finally Fig. 5(c) shows that the increased γ results abrupt collision in NC due to the poor receptions and retransmissions.

Different aspects of improvements in terms of performance such as throughput, energy, delay and collisions are investigated and the result clearly demonstrate the superiority of the CC over NC with only minor exceptions.

5 Conclusions and Future Work

To support the cooperative communications this paper presents an optimized power allocation for WSN based on BFOA algorithm. The algorithm attempts to minimize the power allocation with the constrained receive sensitivity. This approach enhances the throughput, energy and delay performance while comparing with the traditional NC communications in the WSN. The underlying reason of the performance enhancements is due to the fact that the CC enhances the received signal strength with MRC combine. Additionally the power allocation results lower transmit power settings consequently holds the contention limited compared to NC where the contention increases abruptly in high data rates. We intend to extend this research in the network coding paradigm where relays XOR messages from multiple sources and improve the performances in terms of both contention and energy-efficiency.

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