Power allocation in cooperative sensor networks: a stochastic approximation approach

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Abstract: A power allocation technique based on simultaneous perturbation stochastic approximation is devised for wireless sensor networks. Power is such allocated in source and relay that at receiver the desired combined signal strength is attained. The behaviour of the proposed technique is evaluated in a modified simple carrier sense multiple access-collision avoidance-based access control mechanism along with the greedy forwarding approach. Results show the superior performance of the cooperative relay scheme both in throughput and energy gain.

1 Introduction

In cooperative communications, a multiple number of same packets (from the source and from one or multiple relays) are received and combined in the receiver to achieve a better receive signal strength. Accordingly, improved capacity and/or energy performance is achieved in the densely deployed wireless networks. Relay selection and power allocation mechanisms provide vital roles in the cooperative communications paradigm. In cooperative communications paradigm, all the active nodes in the forwarding path may contribute to the cooperative relaying and provide incremental improvement of the receive signal strength. However, the increasing number of relays comes with the bandwidth cost and therefore lowers the capacity. A single best relay or M numbers of best relays are selected by such algorithms to make the cooperative communications practically viable. With M number of best relays where $M+1$ orthogonal channels are employed with a large waste of bandwidth [1]. Consequently, efficient single relay cooperation is often considered [2].

Besides, the power allocation (of source and relay) plays vital role in cooperative communication. Efficiently allocating transmit power achieves energy efficiency; therefore the lifetime of the network in both time division multiple access (TDMA) and carrier sense multiple access (CSMA). TDMA is collision free but necessitates a centralised structure that often does not exist in the sensor network. In CSMA, power allocation is even more important compared with TDMA as such allocation improves the collision performance in addition to the energy efficiency.

The power allocation problem in the cooperative communication remains an open issue. The analytical solutions to such a problem where the objective is to minimise the total power consumption with transmit/receive (Tx/Rx) power constrains are proved to be non-deterministic polynomial-time hard (NP hard) [3]. The proposed algorithm provides an intelligent technique contrary to an analytic solution because of its ability to converge efficiently.

Contrary to the optimal power allocation techniques, the equal power allocation schemes [4] are much simpler but could not provide desirable results [5]. Heuristic approaches [6] are often suboptimal and fail to provide efficient results likewise. Other intelligent techniques such as simulation annealing-based power allocation [7] may provide reasonable performance results but require greater processing power compared with the simultaneous perturbation stochastic approximation (SPSA)-based approach [8].

The aforementioned issues therefore invoke a novel power allocation technique in a single relay, multi-hop, CSMA based, wireless sensor network paradigm and thereby introduced in this paper.

1.1 Contributions

(1) An application addressing the power allocation problem on cooperative communication under constrained receive sensitivity is devised utilising a stochastic approximation.
(2) Energy and throughput performance gain is achieved because of the reduced transmit power and collision probability in distributed wireless networking.

The rest of this paper is organised as follows. Section 2 presents the network and system model, Section 3 presents the proposed power allocation algorithm. Sections 4 and 5 present simulation results in various perspectives and concludes this paper, respectively.

2 Network and system model

Each node i generates packets according to the application requirements and delivers them to the sink $\mathcal{C}$ in multi-hop cooperative paradigm. This section deals with the complementary techniques required along with the core contribution, that is, the power assignment algorithm of cooperative relaying. To specify further, this section outlines the underlying routing technique, medium access control (MAC) algorithm, relay node selection algorithm and finally the selected combining approach in our context.

2.1 Routing

A distributed geographic location aware greedy forwarding algorithm is taken as the underlying routing technique [9]. More precisely, a Euclidian least reaming distance-based routing algorithm is chosen [10]. Let neighbour set N_i is the set of nodes reside in the radio range of node i. Next hop node of i is the node in the set N_i that satisfies $\min(d(N_i, \mathcal{C}))$, where $d(j, k)$ defines the Euclidean distance of nodes j and k.

With a high density of neighbour nodes, a typical characteristic of the cooperative communications paradigm favours choosing this algorithm as such routing performs well in densely deployed scenarios.

2.2 MAC

The proposed system employs CSMA-collision avoidance (CA) with minor modifications where 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. The goal is to provide priority on relaying packets as the relay nodes prioritise cooperatively sending the copy of the packet over its own data packets or the packets it acts as a next hop node to forward.

Otherwise, the same packet will occupy an unnecessary buffer as multiple copies of same packet remain in multiple nodes over the time. We deliberately avoid request to send (RTS)/clear to send (CTS) packet transmissions as we expect that nodes are not transmitting large chunks of data; rather they send small single packet in instances and thereby save resources on sending control packets.

2.3 Relay node

A number of min–max-based relay selection mechanism is devised [11, 12]. We follow the theme of [12] defining our relay selection mechanism where imperfect channel information with the min–max algorithm is utilised while deciding the relay node in the forwarding direction.

Let a packet flow through a path consisting of L_i links. For each L_i, there exists a source S and a destination node D. Selecting a relay particular to that link only considers the neighbours in the forwarding path defined by N_{fi}. Where all the N_{fi} satisfies three conditions (i) are in the radio range of S and D, (ii) located closer to the sink compared with the S and finally (iii) closer to the S compared with the D.

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

2.4 Cooperative relaying

The system employs single relay-based amplify forwarding approach where the relay forwards the packet without detecting the signal (just amplify the power). At the receiver, it employs maximal ratio combining (MRC) as signal combining approach. In general, signal combining adds signals from source and relay and boost the signal quality at the receiver. MRC combines the signal in such way that the gain of each channel is made proportional to the root mean square 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 [13], limited to physical layer characterisation that follows the trend of cooperative communications research where the upper layers are often ignored and sometimes not so important to evaluate (for example, in TDMA case). Different from [13], we evaluate the approach along with the upper layers as we employ CSMA-CA-based approach where the upper layer evaluation becomes crucial.

3 Power allocation

A source node S transfers a packet to the destination D using a relay R. The powers P_S and P_R are assigned to the nodes S and R, respectively, as shown in Fig. 1. The goal is to minimise the total power

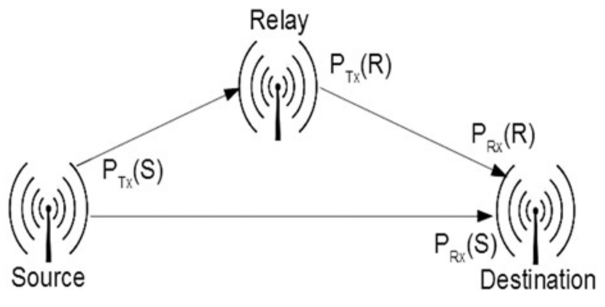

Fig. 1. *Cooperative communication*

assignment $P_{\text{Tx}}(T)$ under the constrained receive sensitivity $P_{\text{Rx}}(\text{Th})$.

If constrained outage probability, that is, maximum allowable outage is defined as $\text{Pr}_{\text{out}}.\text{max}$ and a maximum allowable distance d_{max} from transmitter to receiver that satisfies the minimum reliability level alternately known as outage probability, the mathematical expression becomes $d_{\text{max}} = \max(d{:}\text{Pr}_{\text{out}}(d) <= \text{Pr}_{\text{out}}.\text{max})$. Here $\text{Pr}_{\text{out}}(d)$ is the outage probability at distance d. The outage probability therefore in turn often referred or modelled as the probability of the receive-signal-strength/signal-to-noise ratio is below some minimum value needed for reliable communication [14]. Therefore utilising the readily available receive sensitivity of the receiver suffices the maximum allowable outage criteria utilised in this model.

Consequently, we assign $P_{\text{Tx}}(S)$ and $P_{\text{Tx}}(R)$ such that the sum of the received signal strengths $P_{\text{Rx}}(S)$ (from S) and $P_{\text{Rx}}(R)$ (from R) is greater than the receive sensitivity of the receiver $P_{\text{Rx}}(\text{Th})$. The other constraint is the hardware limit of the transmitter, that is, the highest available power

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

We solve the aforementioned optimisation problem using SPSA [8]. Note that SPSA algorithm works fundamentally on iterative random perturbations and gradient estimations. An SPSA first randomly approximates the parameters that need to be optimised.

The algorithm estimates $\hat{P}_{\text{Tx}}(S)$ and $\hat{P}_{\text{Tx}}(R)$ in dBm that provides us a better view on the values during the development phase. Let the $P_{\text{dBm}} = 10\log(P) + 30$ denote the power in dBm of P. Let $\tau = \aleph(\theta)$ is the penalty cost of θ, where θ consists of $\hat{P}_S$ and $\hat{P}_R$. The gradient vector associated to the cost function measured by $\hat{g} = (\tau^+ - \tau^-)/(2c_k\boldsymbol{\delta})$ is vital in SPSA, where τ^+ and τ^- are evaluated by $\aleph(\theta \pm \text{perturbation})$. $\boldsymbol{\delta}$ is random perturbation vector. And finally $c_k = c/k^{\xi}$; where c, k and ξ are tuning parameters of SPSA.

We define the basic building block of the penalty cost as $\zeta(\hat{P}_{\text{Tx}}(S), \hat{P}_{\text{Tx}}(R)) = P_{\text{Rx}}(\text{Th}) - (\hat{P}_{\text{Rx}}(S) + \hat{P}_{\text{Rx}}(R))$ in case the estimated total receive power is less than the acceptable threshold, otherwise ∞. $\hat{P}_{\text{Rx}}(S)$ and $\hat{P}_{\text{Rx}}(R)$ are estimated received power at the receiver from S and R, respectively. Consequently the final cost is defined as $\tau = \hat{P}_{\text{Tx}}(S) + \hat{P}_{\text{Tx}}(R) + |\log(-\zeta p_{\text{f}})|$. Here p_{f} is the multiplication factor depending on the number of rounds of the algorithmic run. In evaluation, we choose $p_{\text{f}} = 3.01^i$ for the ith round of run. $\hat{P}_{\text{Rx}}()$ can be modelled as $\hat{P}_{\text{Rx}} = \Im(P_{\text{Tx}}, d, \gamma)$ as per Friis transmission equation shown in Fig. 2.

The capability of SPSA's assigning the limit to the approximating parameters helps trivially assigning the hardware minimum and maximum transmit power limit $P_{\text{Tx}}(\text{Min})$ and $P_{\text{Tx}}(\text{Max})$. For a further algorithmic detail please see to the tutorial paper [8].

The technique is preferred to be implemented in the node level so that a large number of control packets beyond a single hop can be avoided. Each time the route changes or the channel condition changes the algorithm needs to rerun.

3.1 Hardware limitations

Transmitter for a low-cost tiny sensor node often does not allow setting the power level to an arbitrary value. It rather has a capability of setting some discrete power levels. n levels of setting are allowed P_1, P_2, P_3, …, P_n. In such a case, $P_{\text{Tx}}(S)$ and $P_{\text{Tx}}(R)$ need to be adjusted to the next level of available power levels $^*P_{\text{Tx}}(S)$ and $^*P_{\text{Tx}}(R)$, respectively.

```
Stochastic power allocation
  θ:(P_Tx(S)_dBm, P_Tx(R)_dBm)
while (Improvement > Threshold)
{
    θ = F(θ)
    {
        Initialise: a, c, l, α, β, ξ
        p = 2
        for k = 1 : l
        {
            a_k = a/(k + β)^α
            c_k = c/k^ξ
            δ = 2 round(random(p, 1)) − 1
            θ+ = θ + c_k δ
            θ− = θ − c_k δ
            τ+ = ℵ(θ+) /* function ℵ() is defined below */
            τ− = ℵ(θ−)
            ĝ = (τ+ − τ−)/(2c_k δ)
            θ = θ − a_k ĝ
        }
        θ = min(θ, P_Min)
        θ = max(θ, P_Max)
        θ = ⌈θ⌉ /* discrete power level only hardware */
    }
}

    τ = ℵ(θ)
    {
        p_f = 3.01^i
        if (P̂_Rx(S) + P̂_Rx(R) > P_Rx(Th))
        {
            ζ(P̂_Tx(S), P̂_Tx(R)) =
            P_Rx(Th) − (P̂_Rx(S) + P̂_Rx(R))
            ℵ = P̂_Tx(S) + P̂_Tx(R) + |log(−ζ p_f)|
        }
        else
            ℵ = ∞
    }

    P̂_Rx = ℑ(P_Tx, d, γ) /* Friis transmission equation */
    {
        λ = v/f
        P_0 = G_T G_R (λ/4π)^γ P_Tx
        P̂_Rx = P_0/(d^γ)
    }
```

Fig. 2 *Stochastic power allocation algorithm*

4 Simulation results

We evaluate the performance of the algorithm in MATLAB. A total number of N sensor nodes are randomly deployed in the squared sensor field F, where $N = 100{:}25{:}300$ in different deployments. The sink is located at the centre of the field. All the nodes in the network generate packets and send data towards the sink using multi-hop routing. We follow Chipcon CC2420 dataset values to simulate the transceiver characteristics [15].

The allowable transmit power setting $P_{\text{dbm}} = [0, -1, -3, -5, -7, -10, -15, -25]$ for this specific hardware. Exponential random backoff algorithm is commonly used to schedule retransmissions after collisions. We set the random backoff as $51.2 \times 10^{-6} \times 2^{\text{BF}-1}(\text{rand}())$ second, where BF denotes the backoff flag incremented in successive collisions. Packets are of 128 B sizes where packet processing time is 2 ms. The retransmission timeout is set to 3. The physical channel is taken as Rayleigh fading channel.

In all the experiments, 200 random deployments are evaluated and averaged. The random deployment is made under the assumption that there exists at least one node in the forwarding path for the next hop and one for relaying. In the case that in a given link there is no relay suitable under the condition $d^{\gamma}_{S,D} > d^{\gamma}_{S,R} + d^{\gamma}_{R,D}$ a non-cooperative (NC) communication takes place. Note that the condition is only valid for low-density deployments.

We evaluate the performance of the power allocation algorithm in terms of throughput and energy efficiency in three different criterions: (i) different packet generation rates, (ii) different field sizes and (iii) different γs. Results in Figs. 3–5 show that in almost all the cases our cooperative communication (C) approach outperforms the traditional NC counterpart.

4.1 Criterion 1

In this deployment, we set the sensor field as 1000 m × 1000 m and the γ is set to 2. The packet generation rate is set to 1 – 4 packet/s.

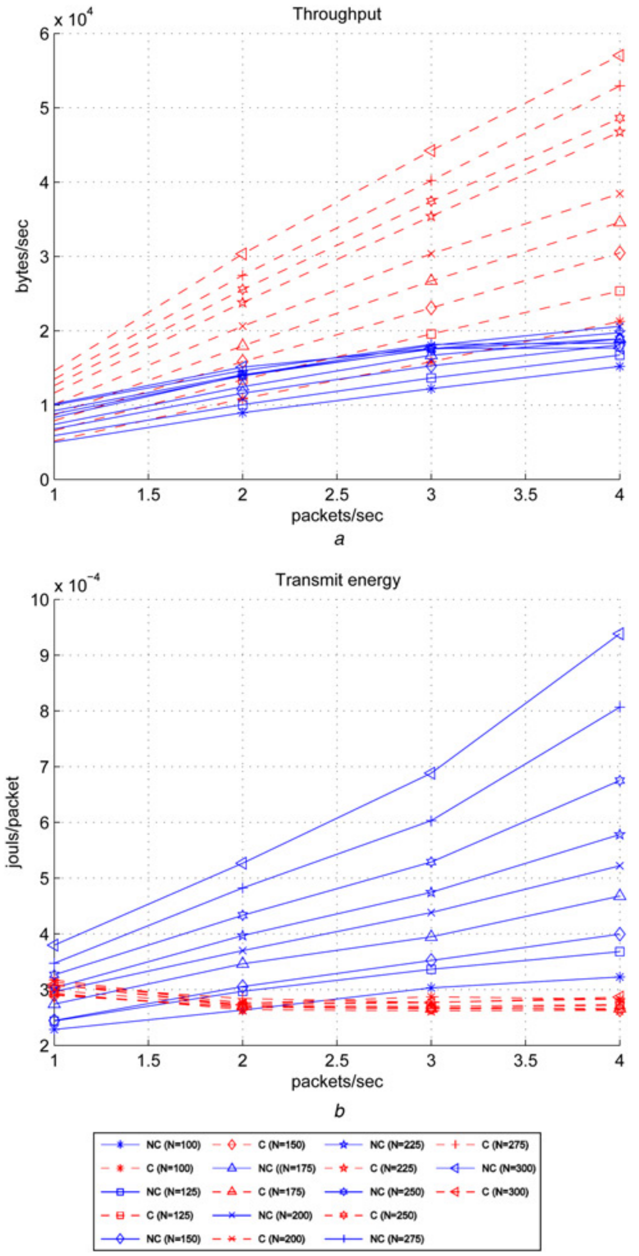

Fig. 3 *Criterion #1*
a Throughput
b Energy dissipation

In all the cases of throughput estimation and collision performance C outperforms NC. Fig. 3 shows that in most of the cases of energy consumption C outperforms NC with minor exceptions.

NC performs better than C if the packet generation rate is low and if the number of nodes in the field is small. With a small number of total nodes there is not enough potential relay nodes available to be selected from, as a result, a poorly located relay cannot perform well in terms of energy efficiency. Even in such condition with a larger packet generation rate, NC performs poorer even in 2 packets/s or above, because of the high collision rate.

4.2 *Criterion 2*

We vary square sized sensor fields as 500:250:1500. We keep γ 2 and set packet generation rate 4 packets/s. Fig. 4 shows that the throughput performance of NC is only comparable when the field length is 500 m. However, with increasing field length the throughput decreases way faster in NC compared with C. In terms of energy consumption C performs better only in 500 m. Note that in this aspect almost all communication are single hop but the situation changes soon after it becomes multi-hop cases where NC never performs well. Owing to the superior resultant signal strength by combining, the success rate at the physical layer is advantageous in C compared with NC. As a result with increasing size of the network in turn increasing hop requirements of travelling data to the destination, the degradation of NC becomes exponentially higher.

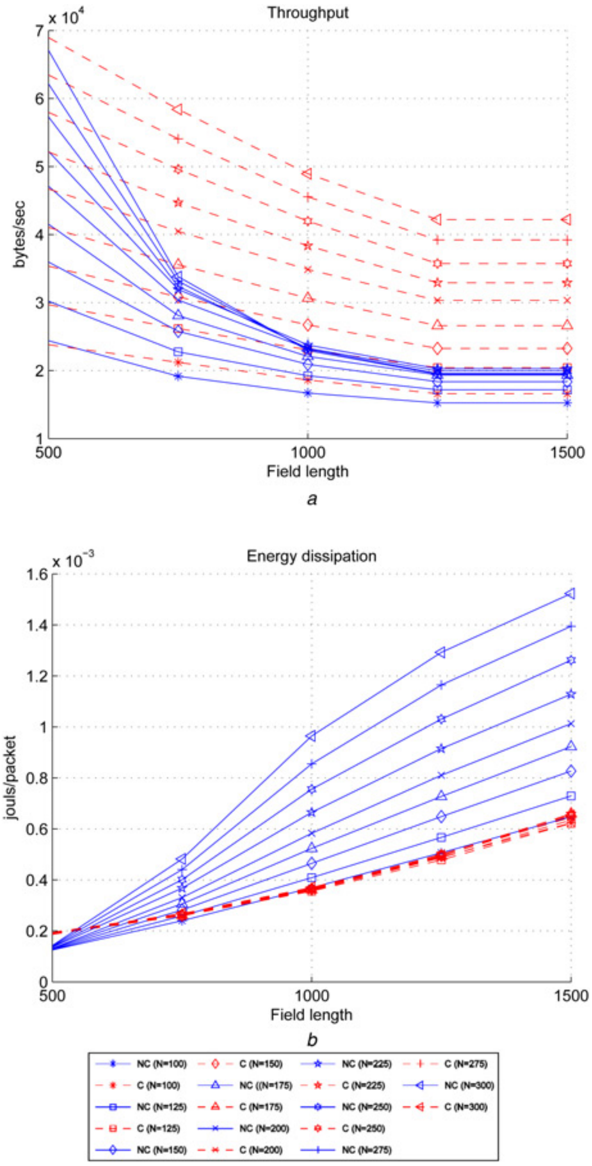

Fig. 4 *Criterion #2*
a Throughput
b Energy dissipation

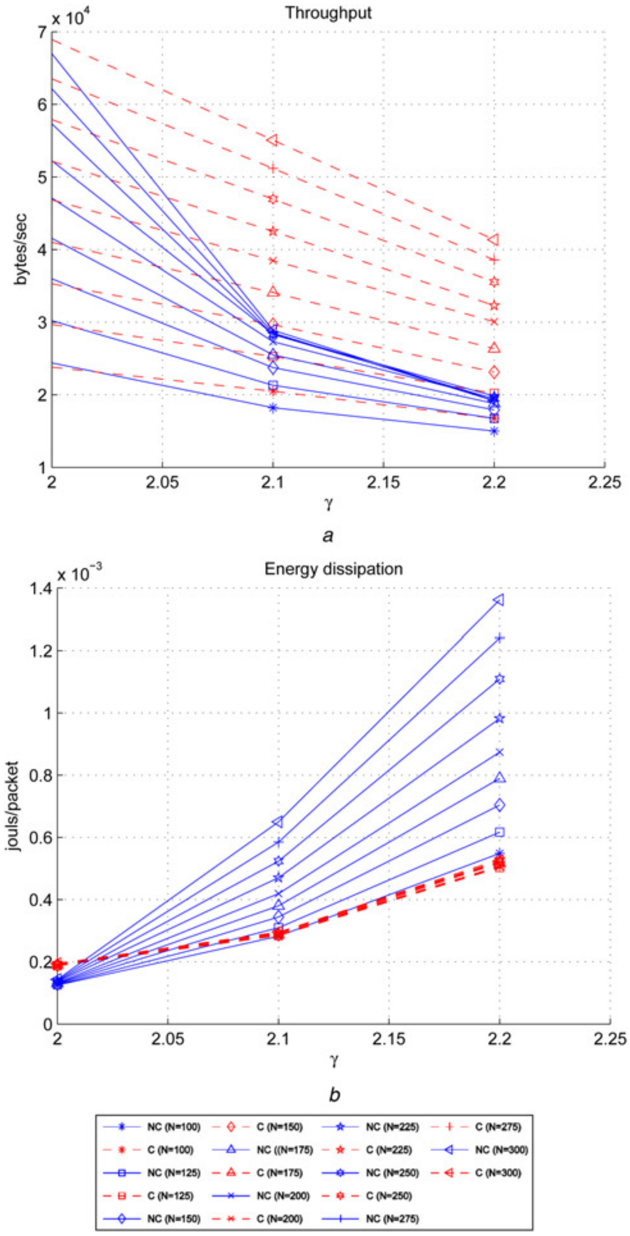

Fig. 5 *Criterion #3*
a Throughput
b Energy dissipation

4.3 *Criterion 3*

In this experiment, we vary γ as 2:0.1:2.2. The sensor field is set to 500 m × 500 m where the packet generation rate is set to 4 packets/s. Again, as above, Fig. 5 shows that only for $\gamma = 2$ NC performs better in energy consumptions, otherwise C dominates the performance. Once again, we understand there exist specific parameters where it needs to rethink whether to cooperate or not [16].

Increasing γ has the similar result of increasing size of the networks as with increasing γ reduces the radio range sharply in effect increases hop.

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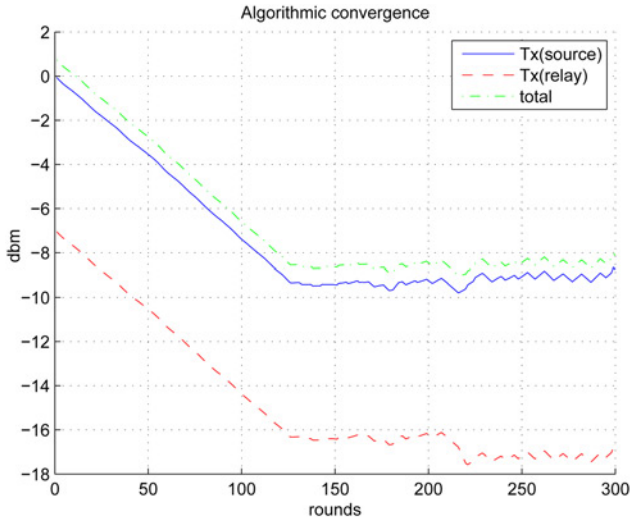

Fig. 6 *Algorithmic convergence*

4.4 Algorithmic convergence

An instance of the algorithmic convergence of the core SPSA technique is shown in Fig. 6. The algorithm converges exponentially during the initial runs. Note that the constant slope rather than an exponential curve is because of presenting the power in decibel milliwatts (dbm) rather than absolute value in watts. Like any other algorithm the typical characteristic holds, where after the convergence with further runs the improvement is minute.

4.5 Rational behind improvements

We further investigate the reasons behind the superior performance of the proposed algorithm by evaluating the collision rate of all the cases in criteria 1, 2 and 3. In almost all the cases, the collision rate of the cooperative communications is negligible compared with the direct transmission. The collision performances of all the criteria are presented in the Fig. 7, where Figs. 7*a–c* depict the collision performances of the criteria 1, 2 and 3, respectively.

In general, NC is incapable of handling a high data rate. In a densely deployed environment with increasing generations,

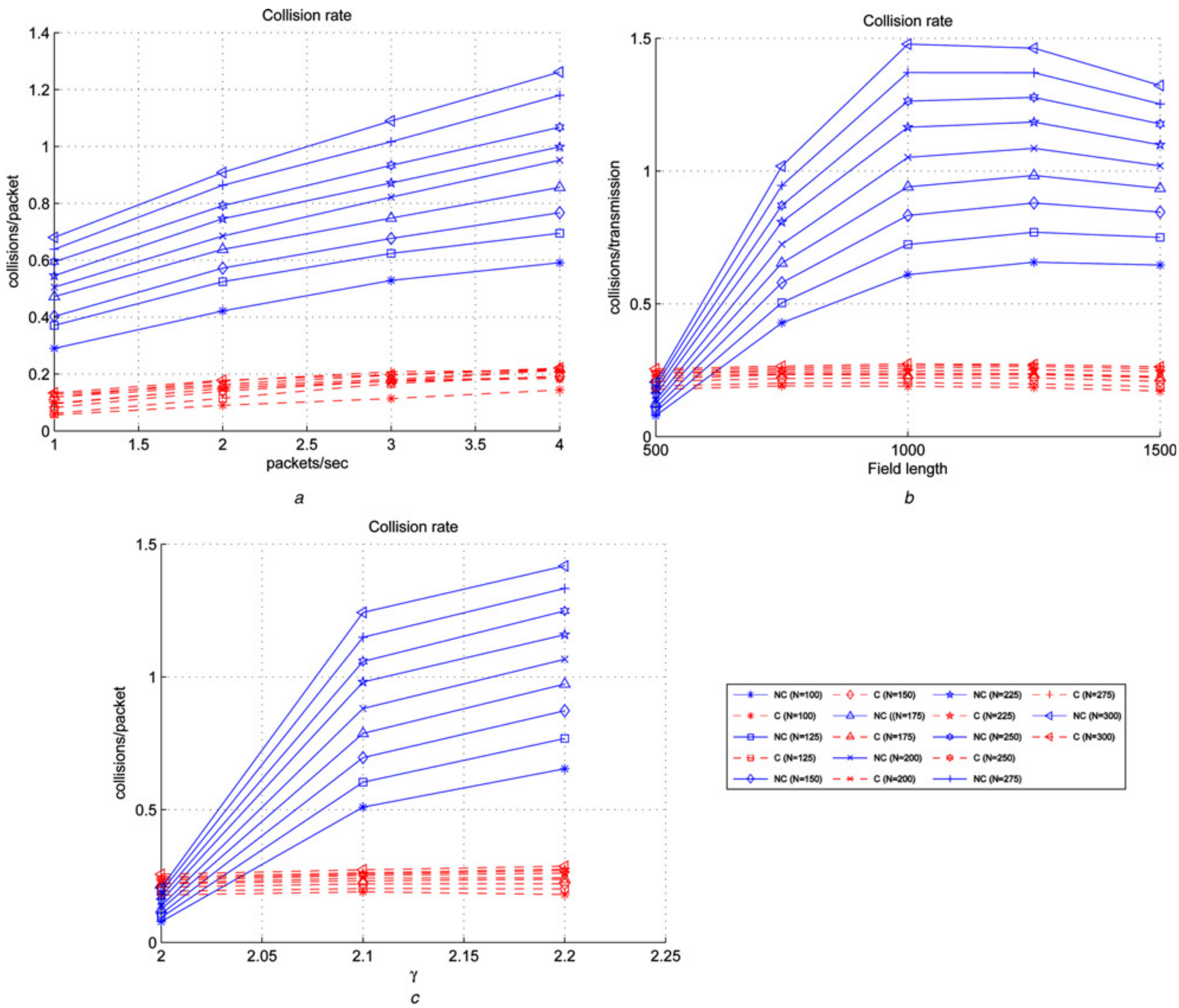

Fig. 7 *Collision ratio*
a Criterion 1
b Criterion 2
c Criterion 3

collision becomes such high that the throughput starts falling where the network performance turns out to be unacceptably degraded. Consequently, energy cost of per packet becomes unacceptably high. With the same hardware, C can handle a much larger number of data packets by providing significant throughput with similar energy exhaustion profile. The evaluations consider a hardware incapable of setting the transmit power to any value. Allowing transmit power set to any value will help C become further efficient.

5 Conclusion

The SPSA technique is utilised to minimise the total power allocation for source and relay nodes in the networks. The power is such allocated that a combined received signal strength is just above the receive sensitivity. Comparison with respect to the NC communication shows the improvement on both throughput and power characteristic can be achieved. A cross-layer design simultaneously handling power assignment with cooperative node section in the network coding paradigm for heterogeneous networks is our future direction of this research.

6 References

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