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Managing Node Collaboration Effectively in Multihop Wireless Sensor Networks for Efficient Data Routing

by

Saurabh Gupta
Dept. of Computer Science & Engineering, Institute of Technology, BHU, Varanasi, India

Arijit Khan
Dept. of Computer Science, University of California, Santa Barbara, California, USA

&

Debashis Saha
Professor, IIM Calcutta, Diamond Harbour Road, Joka P.O., Kolkata 700 104, India

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Saurabh Gupta
Dept. of Computer Science & Engineering, Institute of Technology, BHU, Varanasi, India
saurabh.gupta.cse07@itbhu.ac.in,

Arijit Khan
Dept. of Computer Science, University of California, Santa Barbara, California
arijitkhan@cs.ucsb.edu

Debashis Saha
MIS & Computer Science Group, IIM Calcutta, Joka, D. H. Road,
Kolkata 700104, India
ds@iimcal.ac.in

***Abstract*— As the cost of nodes in wireless multihop sensor networks is decreasing, the density of the network as a whole is increasing due to the deployment of many such sensor nodes that multiplies network connectivity. In this paper, we study the technique of collaborative forwarding to improve the routing connectivity of such networks. Collaborative routing takes advantage of the density of the network to form associations between small connected clusters to relay packets to the next node. The proposed routing scheme, called Controlled Collaborative Optimal Routing (CoCORo), is a novel technique to use opportunistic collaborative communication on top of Trajectory Based Forwarding (TBF) [5] in order to achieve more energy-efficient routing, particularly in dense wireless multihop networks. It is similar to source routing in the sense that the source determines the optimal path consisting of the active nodes and also embeds the trajectory in the packet header. This is done to reduce the energy and the path length. The adjacent non-transmitting active nodes and the low-power-listening mode nodes are dynamically allocated for a controlled opportunistic collaborative communication along the selected path. The scheme successfully improves reliability and capacity gain both by a factor proportional to the number of collaborating nodes. Our work shows that CoCORo significantly decreases the overall energy requirement for the wireless multihop network, and thus provides significant connectivity gain. We focus on analytical techniques to prove the results, and confirm them by performing a numerical evaluation.**

***Keywords*— Wireless Multihop Networks, Sensor Networking, Relay Routing, Cost Optimization, Channel State, Controlled Collaboration, Energy efficiency.**

I. INTRODUCTION

Due to recent developments in wireless communication technologies, small-sized and high-performance computing and communication devices have found better uses in daily life and computing (e.g., commercial laptops and personal digital assistants equipped with radios). A wireless sensor network (WSN) consists of a large number of such low-cost nodes communicating with a base station. The nodes have limited energy and short communication ranges, thus allowing only a few nodes to directly communicate with the base station. Instead, most nodes rely on neighboring nodes to forward their packets to the base station. WSNs include an ever widening array of applications, including sensor networks to monitor, manage, control or sense a given domain; or peer-to-peer ad hoc networking to establish an impromptu communication between mobile terminals without the support of an infrastructure, for instance in emergency response scenarios.

These communications are governed by various routing protocols [1] in the network layers. Popular routing protocols in ad hoc networks have been studied in detail in [2]. The scalability of a routing protocol is crucial as the number of nodes increase. The popular non-geographical routing protocols such as AODV, DSR and DSDV are not scalable. Hence, Trajectory Based Forwarding (TBF) is described in [5] in which the source embeds the route information (termed as trajectory) in the header of the packet and the subsequent intermediate nodes take forwarding decisions based on the trajectory. Further, in the optimal trajectory, the next relay is chosen in such a way that the progress along the trajectory is maximized and also the communication cost of a trajectory is minimized. An optimal trajectory is identified using differential analysis and analogies with geometrical optics [6], [12].

This could have been a good technique of routing if the problems such as traffic congestion, delay, limited capacity of the channel, node failure and path reliability had been well considered. Since multi-hop wireless communication is error-prone, over multi-hop communication is highly unreliable. We propose that along with multihop (MH) routing between successive active nodes selected by TBF, we can effectively employ Opportunistic Space Time collaboration (OST) [7], [11] for better performance. Unlike conventional point to point communications, OST transmission schemes allows different users or nodes in a wireless network to share resources to create collaboration through distributed transmission where each user's information is sent out not only by the user, but also by collaborating users. The goal of this scheme is to exploit a new form of space diversity to combat the effects of channel impairments due to fading; the latter has been termed cooperative diversity. Results show that the joint exploitation of multi-hopping techniques together with node cooperation (at MAC – Medium Access Control - and physical layer) lead to valuable benefits in reducing complexity of routing problems [13]. In other words, non-transmitting active and low-power listening mode nodes must co-operate to maximize network wide objectives (such as reliability, delay and traffic) without compromising their own survivability (as measured by their energy consumption). The nodes in the network have to behave intelligently to find the right tradeoffs between efficient energy consumption and network-wide objectives. We call this new protocol Controlled Collaborative Optimal Routing (CoCORo). We prefer a dense network, since with more nodes added in the network; collaborative method achieves more energy saving compared to traditional non-cooperative shortest path algorithms [14].

The main contributions of our work are the following: 1) we have successfully integrated the TBF [6], [12] with opportunistic collaborative communications [7], [11]; 2) we have adopted a controlled model of collaborative communication, where the trajectory is determined at the source node, and only the nodes adjacent to the trajectory participate in collaborative communication; 3) the overall effect is that we can minimize the path length and energy requirement over those in OST [7], [11] while routing. At the same time, participation of non-transmitting active and low-power listening mode nodes in routing improves the reliability, minimizes delay and reduces congestion over those in TBF [6], [12].

The rest of this paper is organized as follows. The proposed network architecture is described in brief in Section II. The CoCORo protocol with its mathematical model and its advantages over the multi-hop TBF routing have been described in Section III. The optimal trajectory evaluation technique is shown is Section IV. Section V describes the advantage of CoCORo over TBF. A case study and the results are discussed in Section VI. Finally, Section VII concludes the work.

II. NETWORK ARCHITECTURE

We consider the topology to be decentralized ad hoc. Let $V=\{v_1, v_2, \ldots\ldots\ldots v_N\}$ be the set of nodes deployed densely in a 2-dimensional area $\gamma \subseteq \Re_2$. The transmission and reception ranges are equal for a particular node v_i at any instant of time. Let us define it as the communication range $CR(v_i)$ of the node v_i. $CR(v_i)$ varies from node to node as the communication range of the nodes decreases with depletion of their battery power. Hence, a bidirectional edge e_{ij} between two nodes v_i and v_j will exist only when $|e_{ij}| \leq \min\{CR(v_i), CR(v_j)\}$.

We assume that node density, information about the active and low-power listening mode nodes, nearby channel characteristics etc. are known in the entire region and by all nodes in the network [2]-[4]. Since the network is dense, there are redundant nodes in the network. Some nodes will be active for a certain instant of time and the rest will be in low-power listening mode (i.e., in idle mode) in that duration following some synchronization algorithm [8]. The synchronization algorithm must ensure connectivity among the active nodes, total area coverage by those active nodes and the uniform energy distribution among all nodes in the network.

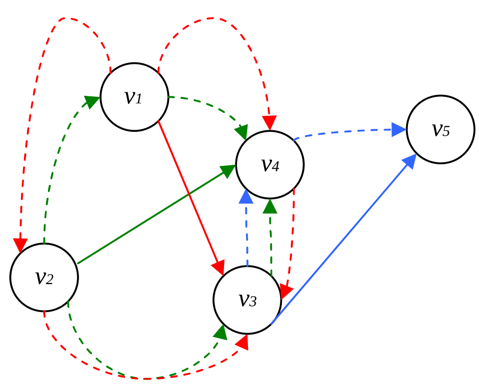

Figure 1: Network Architecture

The network architecture is schematically shown in Fig.1 for 5 nodes. We observe that the nodes v_1, v_2, v_3 and v_4 are in the communication range of each other. Node v_5 is in the communication range of only v_3 and v_4. So, for establishing a communication between the set of nodes $\{v_1, v_2\}$ and v_5, the intermediate nodes $\{v_3, v_4\}$ have to be used. So, if we consider v_1 as the source node and v_5 as the destination node, v_1 will send the data to either v_3 or v_4 or both and then these nodes will forward the data to the destination node v_5. Moreover, the communication can be improved by using the inactive nodes as relays to the destination. For instance, if the data is being sent by v_1 to v_3, the nodes v_2 and v_4 (which will then be in the low-power listening mode) can be used to forward the data to the destination along the routes shown. This is the basic idea of using opportunistic collaboration in wireless networks.

The active nodes have the ability to sense and route data. The low-power listening mode nodes cannot sense data. However, they can be opportunistically used as relay, when data is being forwarded from successive active nodes. The term opportunistic implies that the node will be used only when the overhead of forwarding the data to the next hop is reduced by using it. If the battery power of a node becomes very low, it permanently goes to sleep mode for a certain period of time. A node in sleep mode cannot sense data as well as cannot help in routing [8].

III. CoCORo

The CoCORo protocol integrates opportunistic collaborative communication [7], [11] (by controlled dynamic resource allocation) with the TBF based optimal routing discussed in [6], [12]. We term the adjacent non-transmitting active nodes or low-power listening mode nodes as *relays*.

A node must have the following characteristics to be considered as a relay:

- Its remaining battery power must be higher.
- The flow of traffic through that node must be limited.
- Its distance from the trajectory should be small so that the communication cost is less.
- Its wireless channel from the source must be advantageous for collaborative communication.

At a certain instant of time, if an active node senses some information, it will determine the optimum path to the destination using the TBF algorithm [6], [12]. The optimum path consists of only the active nodes during that time period. Next, the route information is embedded into the header of the data packet by the source node; intermediate active nodes are responsible for forwarding the packet along that trajectory. Selecting the trajectory at the beginning is better than deciding the next hop at each step depending on local energy choices because, in the second case, the path traversed may be quite long, leading to energy depletion at more nodes, while also increasing delay [10].

However, unlike [6], [12], the communication between the selected active nodes in the trajectory is carried out with the necessary help from the adjacent non-transmitting active nodes and low-power listening mode nodes in the network, whenever their wireless channel from the source is advantageous. This ensures an opportunistic cooperative communication between successive hops of the trajectory.

We provide a procedural description of the protocol as follows:

Step 1: Determine the optimal route consisting of active nodes from source to destination that optimizes the three following objectives:

- reduction of the number of hop counts in terms of active nodes,
- reduction of communication cost, and
- increase in the number of relay nodes near the trajectory.

Step 2: Embed the information about the selected active nodes in the data packet and forward it to the next active hop.

Step 3: Whenever an intermediate active node receives the data packet, it forwards it to its next active hop.

Step 4: The relay nodes opportunistically collaborate in communication when the message is being forwarded from one active node to the next.

Steps 1 and 2 are performed by the source node.

A. Channel State

The wireless links among the nodes are modeled as having random, quasi-static Rayleigh fading coefficient $h_{sd} \sim CN(0,1)$ [7]. The overall gain between two nodes is given by:

$$G_{sd} = \rho_0 \left(\frac{d_0}{d_{sd}} \right)^{\alpha} |h_{sd}|^2 \quad (1)$$

where d_0 is a reference distance, d_{sd} is the distance between the two nodes,α is the path loss exponent and ρ_0 is an appropriate constant setting the signal-to-noise ratio (SNR) at the reference distance. Now, to define the channel state *S*, we shall consider a collaborative communication in a simple situation, where v_s and v_d are two successive active hops in the trajectory and v_r is an available relay (Fig. 2).

We consider half-duplex relays that cannot receive and transmit simultaneously, and analyze decode-and-forward (DF) type strategies. Amplitude squares of the channel coefficients, denoted by $a = |G_{s,d}|^2, b = |G_{s,r}|^2$ and $c = |G_{r,d}|^2$ are exponentially distributed random variables with means λ_a, λ_b and λ_c, respectively. We normalize the distance between v_s and v_d, and assume that the relay is located on the straight line joining them (Fig.3).

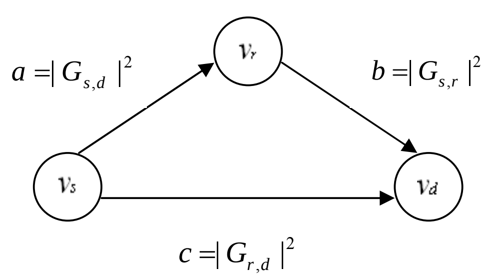

Figure 2: Simple relay model in CoCORo

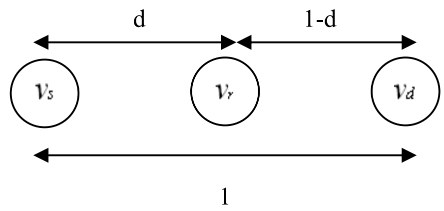

Figure 3: The model for channel State Information

Now the overall network **channel state** S can be defined as a 3-tuple $S = (a,b,c)$ of independent exponential random variables with means $\lambda_a = 1, \lambda_b = \frac{1}{d^{\alpha}}$ and $\lambda_c = \frac{1}{(1-d)^{\alpha}}$ respectively. We assume that the channel state S is known to all the nodes, while the phase information for $G_{s,d}$, $G_{s,r}$ and $G_{r,d}$ is only available at the corresponding receivers. The relay is used when $a \leq b$ and $a \leq c$ [11].

B. Participation Cost

By incorporating a participation cost PC_i to each node v_i , we can analytically model the situation where a node will collaborate in the routing only if the values of its information and the reliability of the reporting path give it a positive payoff, thereby reducing the traffic and improving reliability. PC_i can be modeled as a function $\varnothing$ of events affecting the lifetime of the nodes and the possibility of cooperation; e.g., the remaining battery life B_i , the current traffic flow F_i through v_i, the amount of power P_i required for participating in the current communication, and the channel state information S between the successive active nodes in the trajectory.

$$PC_i = \varnothing(B_i, F_i, P_i, S) \qquad (2)$$

For low-power listening mode nodes, $F_i = 0$. Also PC_i is infinite when $a>b$ or $a>c$ in the channel state S for the corresponding node, since that node cannot be used as a relay in that communication [11].

Now, suppose that $v_s = (x_s, y_s)$ and $v_d = (x_d, y_d)$ are two points in the deployment region γ . v_s and v_d are source and destination respectively for some data-packet. The source node, as stated earlier, will determine the set of active nodes C at that duration of time in order to optimize the three following objectives: i) reduction the no of hop counts in terms of active nodes, ii) reduction of communication cost, and iii) increase the number of relay nodes near the trajectory[5]. To model these characteristics of the trajectory analytically, we define *Communication cost, Progress, Capacity Gain* and *Effective Cost Function* as follows:

Communication cost: Let v_{j1} be an active node on the trajectory P. Let us assume that another active node v_{j2} is within its radio coverage which achieves maximum progress along the trajectory P. We denote the corresponding communication cost as $E(v_{j1}, v_{j2})$, which is the energy spent for the one hop transmission (and reception) of the information packet.

Progress: Let v_{j1} and v_{j2} be the current active hop and the next active hop respectively. Let P_{j1} and P_{j2} be the orthogonal projections of v_{j1} and v_{j2} on the trajectory P, respectively (Fig. 4). The progress along the trajectory P, $l(v_{j1}, v_{j2}, P)$ is defined as the length of the arc on the curve P from P_{j1} to P_{j2} , i.e.

$$l(v_{j1}, v_{j2}, P) = \int_{P_{j1}}^{P_{j2}} ds \qquad (3)$$

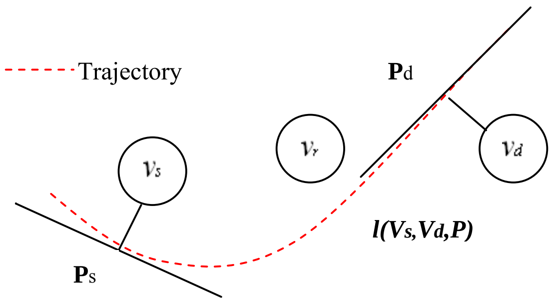

Figure 4: Progress

Capacity Gain: Assume that one node can take part in one communication at a time. In a non-collaborative scenario, active node v_i directly sends data to next active node v_j. Adjacent low-power listening mode nodes do not take part in communication. The resulting Signal to Noise Ratio (SINR) reads:

$$SINR_{v_i,v_j}^{non-collaborative} = \frac{G_{v_i,v_j} T_P}{N_0 B} \qquad (4)$$

where N_0 is the power spectral density of thermal noise, B is the signal bandwidth, and T_P is the transmission power. In a collaborative scenario, let there be n relays collaborating for the transmission from v_i to v_j. Let us denote that set of n relays by V_n. Assuming the signals from different relays add coherently, the resulting SINR reads:

$$SINR_{v_i,v_j}^{collaborative} = \frac{\sum_{v_r \in V_n \cup \{v_i\}} G_{v_r,v_j} T_P}{N_0 B} \qquad (5)$$

Now we can define the capacity region for both non-collaborative and collaborative communications as follows:

$$CP_{v_i,v_j}^{non-collaborative} = B.\log_2(1 + SINR_{v_i,v_j}^{non-collaborative}) \qquad (6)$$

$$CP_{v_i,v_j}^{collaborative} = B.\log_2(1 + SINR_{v_i,v_j}^{collaborative}) \qquad (7)$$

We define the capacity gain $CG_{vi,vj}$ as follows:

$$CG_{vi,vj} = \frac{CP_{vi,vj}^{collaborative}}{CP_{vi,vj}^{non-collaborative}} \qquad (8)$$

Effective Cost Function: The effective cost function $ECF(v_i, v_j, P)$ can be defined as:

$$ECF(v_i, v_j, P) = mean\{\frac{E(v_i, v_j)}{l(v_i, v_j, P) \times CG_{vi,vj}}\} \qquad (9)$$

***Problem Statement*:** The effective cost function for the entire trajectory P can be calculated as:

$$ECF_P = \int_P ECF(v_i, v_j, P)dp \qquad (10)$$

Our objective is to derive a framework for the calculation of the trajectory P consisting of active nodes between nodes v_s and v_d which minimizes the ECF_P given in Eq.(10).

IV. OPTIMAL TRAJECTORY EVALUATION

Let us consider a point $V_i(x, y) \in \gamma$. Then the *ECF* at (*x*, *y*) can be calculated as:

$$ECF(x, y) = \lim_{v_j \to v_i} ECF(v_i, v_j, P) \qquad (11)$$

So Eq. (10) can be rewritten as follows:

$$ECF_P = \int ECF(x(p), y(p))dp \qquad (12)$$

where p is the curvilinear coordinate associated to the trajectory *P*.

Now, the calculation of the trajectory *P* between $V_s = (x_1, y_1)$ and $V_d = (x_2, y_2)$ that minimizes the ECF_P given in Eq (12) is a well-known problem in differential analysis called *problem of variations*. It can be proved that necessary condition for a trajectory to minimize (or maximize) the integral Eq. (12) is that the following relationships, called *Euler's equations* are satisfied:

$$\frac{d}{dp}(ECF.\frac{dx}{dp}) = \frac{\delta ECF}{\delta x} \qquad (13)$$

$$\left(\frac{dx}{dp}\right)^2 + \left(\frac{dy}{dp}\right)^2 = 1 \qquad (14)$$

A simple closed solution is obtained in case of geometrical optics in [8]. Using the similarity, we can say that a point O =(x_0, y_0) in the deployment region γ can be identified such that in any point P = (*x*, *y*), the *ECF* only depends on the distance between P and O, i.e.

$$ECF(x, y) = ECF\left(\sqrt{(x - x_0)^2 + (y - y_0)^2}\right) \qquad (15)$$

In polar coordinates, considering O as origin and P = (*r*, *θ*) , Eq. (15) can be rewritten as:

$$ECF(r, \theta) = ECF(r) \qquad (16)$$

Now, it can be proved that the trajectory which minimizes the optical path satisfies the following relationship:

$$\theta = k.\int_0^r \frac{dr}{r.\sqrt{\{ECF(r)\}^2 r^2 - k^2}} \qquad (17)$$

where *k* is an appropriate constant. Now, we can determine the ∞^2 curves which satisfy Eq. (17), however only one of them passes for both $V_s = (x_1, y_1)$ and $V_d = (x_2, y_2)$ as required by the problem of variation.

Proof of Optimality: Now we prove that the optimality of the scheme is not compromised by using the opportunistic collaboration.

Theorem 1: A relay node between two active nodes can be as much as $\sqrt{3}$ times away from the trajectory than either of the active nodes it connects.

Proof: We follow the Rule B from [6] which states that if the active node forwarding the packet is on the left(right) of the trajectory, and at some distance *V* from it, then the next active node to receive the packet cannot be also on the left(right) of the trajectory and at some distance *V' >V* from it. So, we may conclude that the maximum distance that an active node will have from the trajectory will be equal to its communication range R. Now, we find out the maximum distance that a relay node can have from the trajectory. For this we take two active nodes and a relay node connecting them as shown in Fig. 5.

In the figure, S is the source node, D is the destination node and N is the relay node between them. Let the communication ranges of S, D and N be R_1, R_2 and R_3 respectively. So the maximum distances for the following will be:

SD=min(R_1,R_2),

SN=min(R_1,R_3),

ND=min(R_2,R_3)

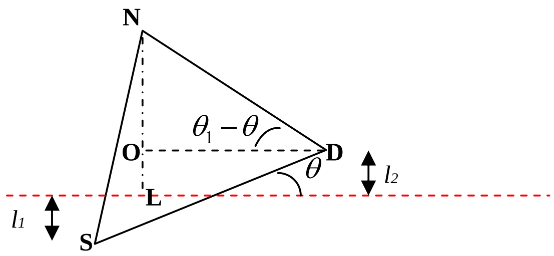

Figure 5: Proof of Optimality

SD is inclined at angle θ from the trajectory (assumed to be a straight line for easy calculations). So the distance

$(l_1+l_2) \leq$ SD sin θ

$\Rightarrow l_2 \leq$ SD sin θ. (18)

Now, distance of the relay from the trajectory NL will be:

NL=NO+OL (19)

For $\theta<\pi/2$,

NL = ND.sin (θ_1-θ) +l_2

$\leq$ ND.sin (θ_1-θ)+SD sin θ

Now, for maximizing this distance let us consider the case ND=SD=NS=R, such that $\theta_1=\pi/3$. So,

NL$\leq$2R.sin ($\theta_1/2$).cos((θ_1-2θ)/2).

on maximizing NL w.r.t θ, we get $\theta=\pi/6$

Hence, NL$\leq$R (20)

In another scenario, where $\theta>\pi/2$,

NL = ND.sin ($\pi+\theta_1$-θ) +l_2

$\leq$ SD sin θ -ND.sin (θ_1-θ)

Again,

NL$\leq$2R.cos ($\theta_1/2$).sin((2θ-θ_1)/2)

and on maximizing, we get

NL$\leq\sqrt{3}$ R (21)

Hence, by Eq (20) and Eq. (21), we see that the relay node can be at most $\sqrt{3}$ R distance away from the trajectory. So, the optimality of the scheme is not compromised by the opportunistic collaboration.

Cost-Benefit Balance: We, now calculate the cost-benefit balance function of the collaborative approach compared to the single-hop approach. We consider the energy-constrained network such that the cost of each transmission is given by:

$$E = ad^b + c, \quad (22)$$

where d is the distance between the transmitter and the receiver, c is the energy consumed in electronics of the transmitter and receiver, which is independent of the transmission distance and the exponent b has a value in the range (2,6), depending on the environment[6].

Consider a source-destination pair ; in TBF, the energy cost needed for the transmission will be single-hop energy cost. Moreover we normalize the scheme as in Fig. 3 such that the distance between the source and the destination is unity. So, the non-collaborative energy will be:

$$E^{non-collaborative} = a + c \qquad (23)$$

Now, for CoCORo model, let us assume n relays places at distances $d_1, d_2, \ldots, d_n$ from the source node s. The total energy needed in this transmission will be:

$$E^{collaborative} = E_{s,r}^{collaborative} + E_{r,d}^{collaborative} \qquad (24)$$

According to [14],

$$E_{s,r}^{collaborative} = a.\max(d_1{}^b, d_2{}^b, \ldots d_n{}^b) + nc \qquad (25)$$

and

$$E_{r,d}^{collaborative} = a.\frac{1}{\sum_{i=1}^{n} \frac{1}{(1-d_i)^b}} + nc \qquad (26)$$

We take the expected value of all the relay distances from the source as d, such that the energy needed in cooperative transmission becomes:

$$E^{collaborative} = ad^b + a\frac{(1-d)^b}{n} + 2nc \ , \qquad (27)$$

Now, we calculate the optimum value of n such that the energy cost is minimized. The Cost-Benefit Balance function is hence, defined as,

C.B = $E^{non-collaborative}$ - $E^{collaborative}$

$$= a(1 - d^b - \frac{(1-d)^b}{n}) + (1-2n)c \qquad (28)$$

differentiating w.r.t. n,

$$\frac{\partial(C.B)}{\partial n} = \frac{a(1-d)^b}{n^2} - 2c$$

equating this to zero, we get the value of n.

$$n = \sqrt{\frac{a(1-d)^b}{2c}}$$

again differentiating,

$\frac{\partial^2(C.B)}{\partial n^2} = -\frac{2a(1-d)^b}{n^3}$, which is always <0. Hence, we have a maxima.

From Eq. (28), we obtain the optimum value of n which comes out to be:

$$n = \sqrt{\frac{a(1-d)^b}{2c}} \qquad (29)$$

Hence, for this value of n, we have the minimum energy cost in collaborative scenario.

Figure X shows the variation of C.B with n. We assume that a=90mW, b=3.1, c= 4×10^{-2} mW, d=0.3. We see that the value of n for minimum C.B comes at around 19 which is confirmed by Eq. (29) to be 19.29. Hence for this model, we should use 19 relays between two active nodes for minimum energy cost.

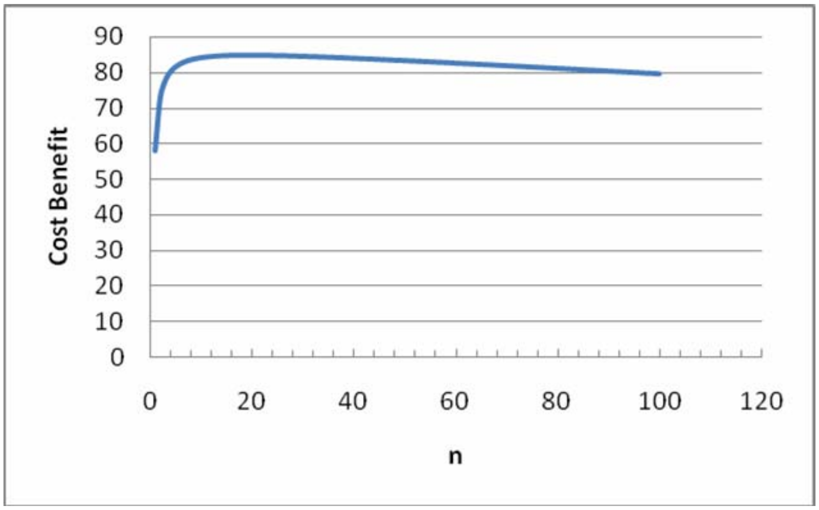

Figure 6: Cost Benefit Vs. n in CoCORo

V. COMPARISON WITH TBF

A. *Capacity Gain*: We have defined the capacity gain $CG_{vi,vj}$ earlier as follows:

$$CG_{vi,vj} = \frac{CP_{vi,vj}^{collaborative}}{CP_{vi,vj}^{non-collaborative}}$$

$$= \frac{B.\log_2(1+SINR_{vi,vj}^{collaborative})}{B.\log_2(1+SINR_{vi,vj}^{non-collaborative})}$$

$$\approx \frac{SINR_{vi,vj}^{collaborative}}{SINR_{vi,vj}^{non-collaborative}}$$

$$= \begin{cases} 1 & n<1, \\ n & otherwise \end{cases} \qquad (30)$$

[Using Eq. 4, 5 and assuming equal gain over all relays]
Thus, Eq. (30) shows the **capacity gain in CoCORo over the multi-hop TBF routing** described in [6], [12].

B. *Reliability Gain*: CoCORo improves reliability of successful message delivery by a factor proportional to the number of relay between two successive hops in the trajectory. The situation is shown below (Fig. 7):

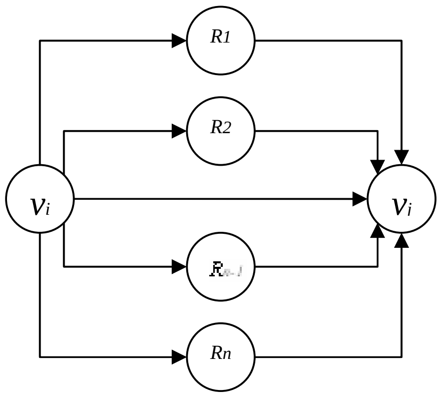

Figure 7: Relay Gain

When conventional MH routing is done over the selected active nodes, the number of path between any two successive active nodes, say, V_i and V_j is one. However, in CoCORo, there are n relay nodes collaborating in the communication between V_i and V_j. Thus, the reliability of message sending is increased by a factor of n over [6], [12].

C. *Gain vs. Participation Cost:* As can be seen in the Fig.8, the CoCORo protocol provides both the energy benefit and the reliability gain. For low values of *n*, the reliability gain and capacity gain are low and also, the participation cost will be high which is not favorable. For large values of *n*, the reliability gain and the capacity gain will be high, but at the same time, the participation cost will be again, high. For an optimum value of *n* given by Eq.(29) we get sufficiently high gains and the participation cost. Moreover, the value of *n* can be varied according to the need of the network. For Example, for a fixed maximum participation cost, we can study the Fig.8 for the optimum value of *n* having the highest gain in reliability and capacity.

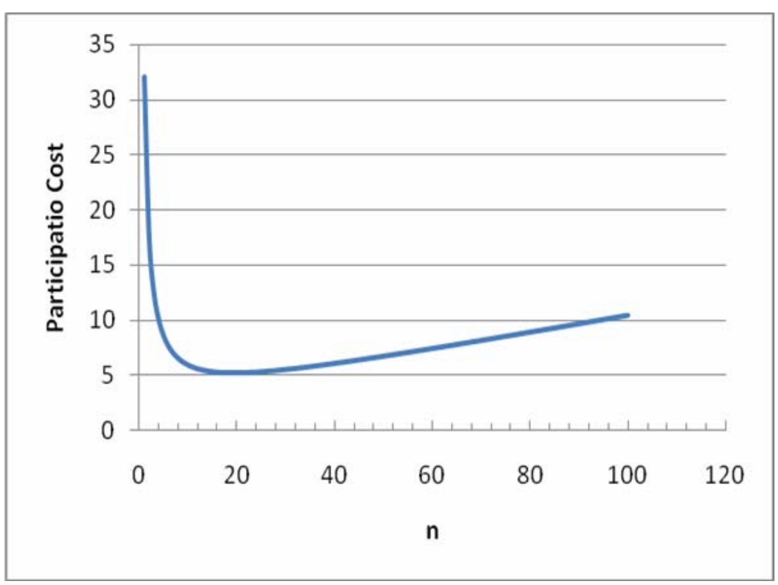

Figure 8: Participation Cost Vs Gain

Now, we provide the pseudo-code for the implementation of CoCORo:

```
Procedure Node;
Begin
While (Packet Received)
    If (Node is Source)
        Formulate trajectory optimizing hop counts, communication cost and number of
        relay nodes using Eq. (17);
        Embed the trajectory in packet header;
        Embed the information of selected active nodes in the packet header;
    Else
        Access the packet header;
        If (Node is not Destination)
            Transmit();
End Node;

Procedure Transmit;
Begin
If (Node is Active node)
        Find optimum relays satisfying the trajectory (Eq.17) and satisfying the channel
        gain conditions[11];
        Select n best relays according to Eq. (29);
        Send the packet to these n relays;
Else if (Node is Relay)
        Find the next active node on the trajectory;
        Send the packet to the next active node;
End Transmit;
```

VI. CASE STUDY AND RESULTS

We assume that in the coverage area of a node $V(x,y) \in \gamma$, the active and low-power listening mode nodes are Poisson distributed.

Then, inside that area, one-hop communication cost E, active node density ρ_a and relay node density ρ_r remain constant. Then, using Eq. (9) and Eq. (11), we get:

$$ECF(x,y) = \frac{E}{mean\{\Delta l(x,y)\} \times mean\{\Delta CG(x,y)\}} \tag{31}$$

In [12], it has been proved that,

$$mean\{\Delta l(x,y)\} = R - \int_0^R e^{-\rho_a(x,y).[R\cos^{-1}\left(\frac{u}{R}\right) - u.\sqrt{R^2-u^2}]} du \tag{32}$$

where R is the range of Vi and the probability distribution function is as follows:

$$\Pr\{\Delta l(x,y) \le u\} = e^{-\rho_a(x,y).\psi_2} \quad (33)$$

In Fig.9, we have shown a node Vi on the trajectory. The circular region represents the coverage area of Vi. Suppose the next active node along the trajectory is at a distance u ($0 \le u \le R$) from Vi. So we are concerned with the mean number of relay nodes in the region Ψ_1 (Fig.9). Since we have assumed that ρ_r remains constant inside the coverage area of Vi, then for n>1,

$$mean\{\Delta CG(x,y)\} = \rho_r(x,y).\int_0^R R\left(2 - \frac{u^2}{R^2}\right)du \quad = \frac{5R^2}{3}.\rho_r(x,y) \quad (34)$$

From Eq. (31), we have:

$$ECF(x,y) = \frac{E}{\left(R - \int_0^R e^{-\rho_a(x,y).\left[R\cos^{-1}\left(\frac{u}{R}\right) - u.\sqrt{R^2-u^2}\right]} du\right) \times \frac{5R^2}{3}.\rho_r(x,y)} \quad (35)$$

For this modeling, we can substitute the right hand side of Eq. (34) in Eq. (15) to evaluate the optimal trajectory. Clearly, both the **capacity gain and reliability gain of CoCORo over TBF are given by** $\frac{5R^2}{3}.\rho_r(x,y)$ **given that this value is greater than 1.**

Next, we shall compare the capacity gain of CoCORo over TBF for the case when node density is a function of r, the distance from the centre, according to a Gaussian distribution,

$$\rho_r(r) = K.e^{-\frac{r^2}{2a^2}} \quad (36)$$

The capacity gain as a function of r is shown in Fig. 10 for the two protocols. We assume that $K = 4.5\times 10^{-4} m^{-2}$, a=600m, R=110m, and the normal channel capacity for multi-hop TBF routing = 1Mb/s.

Moreover, the variation of capacity gain with the average battery power left in the nodes is shown in Fig. 11. Here, we have assumed that the relay node density is constant at $4.5\times 10^{-4} m^{-2}$ and the maximum range for all nodes is 500m at full battery power which linearly decreases with the depletion in the battery power.

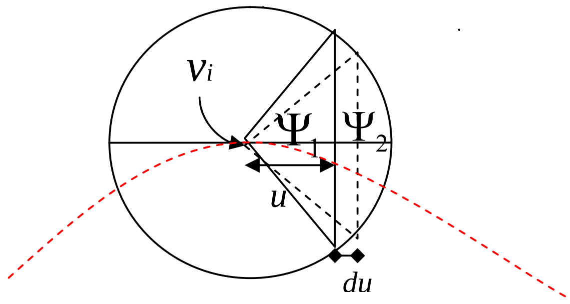

Figure 9: ECF(x,y) calculation

VII. CONCLUSIONS

We have shown how opportunistic collaborative communication can be embedded in trajectory based forwarding in a controlled manner to achieve smaller hop count, effective energy usage, higher capacity, and higher reliability. Our CoCORo protocol will be extremely useful in dense networks, where we can effectively employ adjacent low-power listening mode nodes as relays. Currently, we are working on the possibilities of different types of Opportunistic Collaborative Communication models [11] that can be embedded in this CoCORo model.

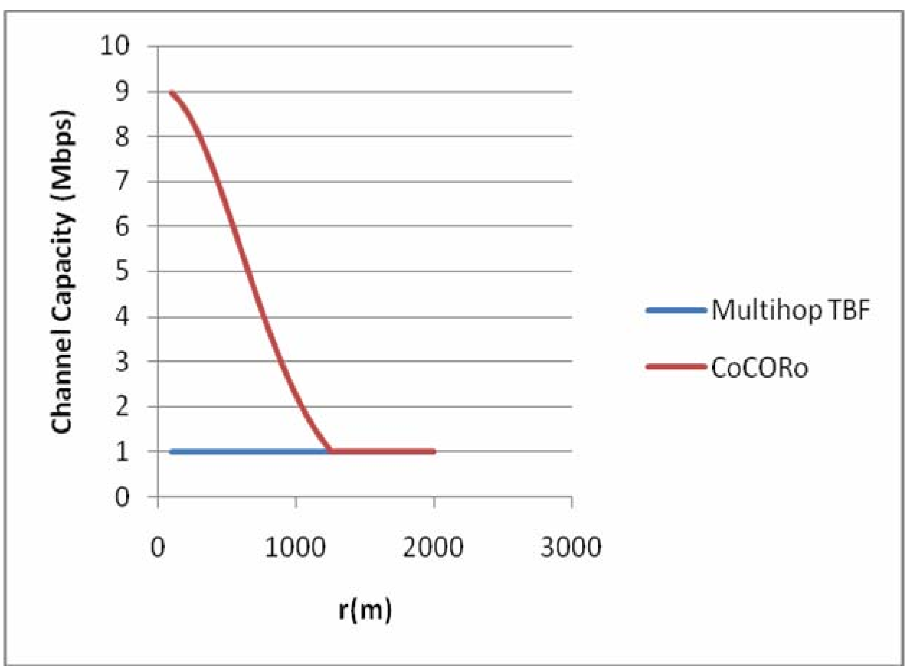

Figure 10: Channel Capacity Vs. r in CoCORo and TBF

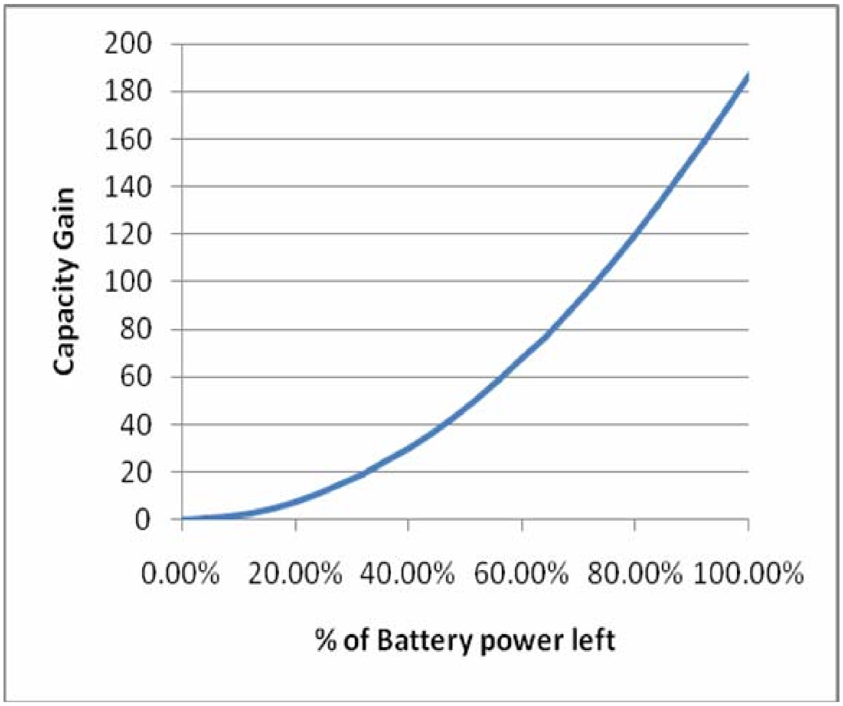

Figure 11: Variation of Capacity gain with battery power

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