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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

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

We provide a procedural description of the protocol as follows:

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:

$$G_{sd} \qquad {}_{0} \frac{d_0}{d_{sd}} \qquad | h_{sd} |^2$$

Capacity Gain: Assume that one node can take part in one communication at a time. In a non-collaborative scenario, active node vi 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:

$$SINR_{v_i,v_j}^{non\ \ collaborative} \qquad \frac{G_{v_i,v_j}T_P}{N_0B} \tag{4}$$

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 vi 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:

$$SINR_{\mathrm{ijv:}\ j} \qquad \frac{\begin{array}{c} G_{r\quad j}T \\ {}_{r\quad n\quad i} \end{array}}{N\ B}$$

IV. OPTIMAL TRAJECTORY EVALUATION

Let us consider a point $V_i(x, y)$.

SD is inclined at angle T¡ C4'0YG "V&F "Đ T

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:

$$E^{non \quad collaborative} \qquad a \quad c \tag{23}$$

Now, for CoCORo model, let us assume *n* relays places at distances d_1, d_2

Figure X shows the variation of C.B with n. We assume that a=90mW, b=3.1, c=$4 \quad 10^{2}$ 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.

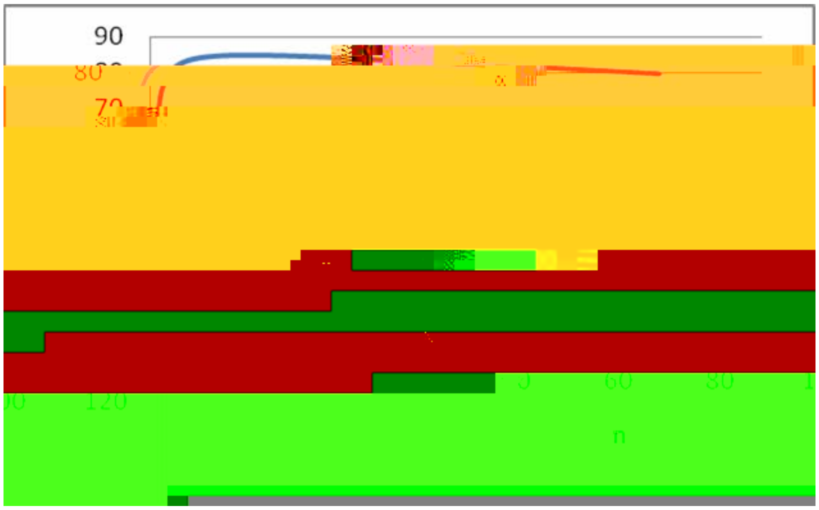


Figure 6: Cost Benefit Vs. n in CoCORo

V. COMPARISON WITH TBF

A. Capacity Gain: We have defined the capacity gain CGvi,vj earlier as follows:

$$CG_{vi,vj} \quad \frac{CP^{collaborative}_{vi,vj}}{CP^{non \quad collaborative}_{vi,vj}}$$

$$\frac{B.\log_2(1 \quad SINR^{collaborative}_{vi,vj})}{B.\log_2(1 \quad SINR^{non \quad collaborative}_{vi,vj})}$$

$$\frac{SINR^{collaborative}_{vi,vj}}{SINR^{non \quad collaborative}_{vi,vj}}$$

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

[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):

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

VI. CASE STUDY AND RESULTS

We assume that in the coverage area of a node $V_{(x,y)}$, the active and low-power listening mode nodes are where *R* is the range of V_i and the probability distribution function is as follows:

$$\Pr\{\ \ l(x,y)\quad u\}\quad e^{\ {}_{a}(x,y).\ \ {}_{2}} \tag{33}$$

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 $\ u\ $ *R*) from Vi. So we are concerned with the mean number of relay nodes in the region (Fig.9). Since we have assumed that ${}_r$ remains constant inside the coverage area of V_i, then for n>1,

$$mean\{\ \ CG(x,y)\}\qquad {}_r(x,y).\ {}^{R}_{0}\ R\ \ 2\ \ \frac{u^2}{R^2}\ du\qquad \frac{5R^2}{3}.\ \ {}_r(x,y) \tag{34}$$

From Eq. (31), we have:

$$ECF(x,y)\quad \frac{E}{R\ \ {}^{R}_{0}\ e^{\ {}_{a}(x,y).\ R\cos^{1}\ \frac{u}{R}\quad u.\sqrt{R^2\ \ u^2}}\ du\qquad \frac{5R^2}{3}.\ \ {}_r(x,y)} \tag{35}$$

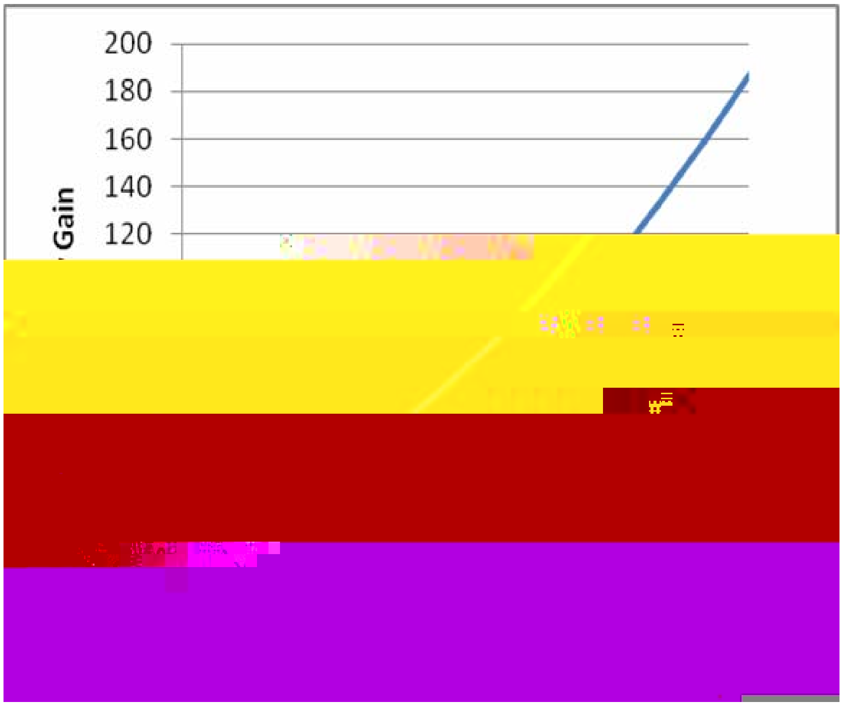
For this modeling, we can substitute the right hand side of Eq. (34) in Eq. (15) to evaluate the optimal trajectory. Clearly, both the **capacity gain and reliability gain of CoCORo over TBF are given by** $\frac{5R^2}{3}.\ \ {}_r(x,y)$ **given that this value is greater than 1.**

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,

$${}_r(r)\quad K.e^{\frac{r^2}{2a^2}} \tag{36}$$

The capacity gain as a function of r is shown in Fig. 10 for the two protocols. We assume that *K* $4.5\ \ 10^{4}m^{2}$, *a*=600*m*, *R*=110*m*, 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 $10^{4}m^{2}$ and the maximum range for all nodes is 500m at full battery power which linearly decreases with the depletion in the battery power.



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