# Maximizing Transported Data in a Wireless Sensor Network: How Much can the Network Transport Before Partition?

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*Abstract*—We consider a scenario where the communication nodes in a sensor network have limited energy, and the objective is to maximize the aggregate bits transported from sources to respective destinations before network partition due to node deaths. This performance metric is novel, and captures the useful information that a network can provide over its lifetime. The optimization problem that results from our approach is nonlinear; however, we show that it can be converted to a Multicommodity Flow (MCF) problem that yields the optimal value of the metric. Subsequently, we compare the performance of a practical routing strategy, based on Node Disjoint Paths (NDPs), with the ideal corresponding to the MCF formulation. Our results indicate that the performance of NDP-based routing is within 7.5% of the optimal.

*Index Terms*—Network Partition Time (NPT), Maximal Independent Sets(MIS), Node-disjoint Paths (NDPs), Link-Contention graph (LCG)

## I. INTRODUCTION

The model we consider in this paper is motivated by a wireless sensor network deployed for soil moisture monitoring in a semi-arid region in the state of Karnataka in South India [1], [2], [3]. The sensors are embedded at chosen spots where moisture is to be measured. Usually, the chosen spots are well-illuminated by sunlight, so that solar panels can be used to supply energy to the sensors and associated electronics. The data collection point or Base Station (BS) is several hundred meters away, and is assumed to be close to an electrical outlet.

The area between the spots being monitored and the BS is covered by a multihop wireless communication network. However, there are constraints on the placement of the communication nodes; for example, there may be patches of ground that are well-illuminated, but inaccessible (for example, a patch of well-illuminated ground may be walled off as it belongs to a third party). This forces the communication nodes to be located at spots that may be illuminated poorly. In our *model*, we capture these realistic aspects by assuming that sources and destinations are equipped with infinite energy, but the communication nodes have access to finite supplies of energy only.

Given such a network, we are interested in *maximizing* the bits transported from source(s) to destination(s) before the communication network runs out of energy. A solution with high throughput, but low network lifetime may not be good for our application scenario; similarly, a solution with long network lifetime, but low throughput may be undesirable: A network may remain idle for most of the time claiming a higher *Network Partition Time* (NPT), but the *useful* data transferred might be substantially less. Therefore, we seek to maximize the *product*, which is the aggregate bits transported before network partition.

Sensor networks have wireless links. Links that interfere cannot be activated simultaneously. We utilize the notions of *maximal independent sets* (MIS) in the *link contention graph* [4] to obtain an *equivalent wired network model*. Then, we study the problem of route selection in this equivalent wired network model so that the objective, *viz.*, aggregate bits transported, is maximized, subject to the nodes' "available energy" values. We show that the problem of maximizing the aggregate bits transported before network partition can be formulated as a Linear Program. Next, we consider a routing strategy based on the *maximum number of Node Disjoint Paths between each source-destination pair*, and compare its performance with that of the ideal above. We find that the NDP-based strategy is able to transport an aggregate number of bits that is within 5%–7% of the optimal, indicating that it is a promising strategy.

The contributions of this paper are as follows.

- The metric that we seek to optimize, *viz.,* aggregate bits transported before network partition, is natural. However, to the best of our knowledge, the metric has not been used in the literature.
- The equivalent wired network model results after all wireless-specific aspects (link technology, MAC duty cycles, transmit powers) are encapsulated into a module. The resulting model makes it easier to analyse the performance of routing strategies, in terms of aggregate bits transported, with limited nodal energies.

- We show that the our problem can be recast as a Linear Program (a Multicommodity Flow problem), even though the original formulation results in a nonlinear program.
- We examine the performance achievable by a practical routing protocol based on the principle of Node Disjoint Paths (NDPs). Our results indicate that this protocol performs well, achieving an aggregate bit transfer within 7.5% of the ideal value given by the Multicommodity Flow problem.

In Section II, we survey the related work. The models we study in this paper are introduced and analyzed in Section III. A practical routing protocol is discussed in Section IV. Section V compares the performance of the routing protocol, in terms of aggregate bits transported, with the ideal obtained from the models in Section III. We conclude in Section VI.

## II. RELATED WORK

Our application context requires sources to send data to the destination at regular intervals. In this context, the "pull" model of operation, where the network sends data only in response to queries from the outside, does not seem appropriate; this is because queries would have to be sent repeatedly, leading to avoidable energy expenditure. So, a lot of the query-based protocols in the literature are difficult to utilize. Further, our objective is to maximize the (weighted) aggregate bits transferred before network partition, and we are unaware of any work that considers this metric while designing protocols. Consequently, the protocols we survey below do not really address our concerns. Nevertheless, for completeness, we discuss several prominent routing protocols in the rest of this section.

In [5], Heinzelman et al. proposed a variant of flooding, SPIN, which disseminates data from one node to every other node, so that, when needed, required data can be extracted from any of the nodes. In our context, replication of data at various nodes is hardly required. Moreover, SPIN does not guarantee reliable data delivery [6].

Both Directed Diffusion (DD) [7] and its variant Gradient Based Routing (GBR) [8] are event-driven protocols, that supply data in response to external queries. Both of them use in-network aggregation. In [9], Yao et al. discussed COUGAR, which is a query-driven, in-network aggregation based protocol in which a group of nodes choose a leader node who aggregates their data and sends to Base-Station. ACQUIRE [10] is similar. However, as mentioned before, event-driven protocols are not natural in our application scenario.

Similar to DD, in [11], Ganesan et al. presented a Braided Multipath Routing Protocol, which has 50% more fault resilience as compared to the Node-Disjoint Multipath protocols, but it uses only one path for data transfer; hence the overall bits transferred is limited by the capacity of a single path. Shah and Rabaey in [12] suggested the alternative-route routing paradigm. Data is routed via primary path, in an energy efficient way; if a fault occurs, alternative-route is chosen for data transfer.

A sensor network multipath version of AODV, AOMDV [13], routes along multiple link disjoint paths, where route-discovery is done through flooding, which is not energy-efficient [14]. In some protocols, for the sake of improving reliability, multiple instances of a single packet are routed through multiple paths. Examples are ReInForm [15], MCMP [16], ECMP [17]. ReInForm provides reliability at the cost of high-energy dissipation. MCMP tries to optimise for reliability and delay, but is highly interference-prone, which limits successful data transmissions. ECMP, in addition to MCMP, optimises for energy-efficiency too, but the packet delivery ratio for ECMP equals that of MCMP. Various protocols which use packet splitting as a packet salvaging technique like $N$ to 1 Multipath [18], or for Forward Error Check like, EQSR [19], H-SPREAD [20] suffer heavily due to interference.

Moving to protocols following the node-disjoint routing paradigm: NDMR [21] chooses three least hop, node disjoint paths (even if many paths exist) for routing, and switches to other paths if any of these three paths fails. REER [22] routes data along two paths; primary path and alternate path, which are selected on the basis of link-cost. The interference-free routing protocols like, I2MR [23], EECA [24], limit the number of paths assigned for routing data to three and two, respectively. In [25], Radi et al. came up with a throughput aware multipath node-disjoint protocol; however, it is event-driven.

In summary, none of the protocols mentioned here raises the question of "maximising aggregate bits transported before network partition." In many cases, the scenario addressed is such that this question does not arise naturally (*e.g.*, application scenarios where minimizing delay is the main objective).

## III. NETWORK MODEL AND ANALYSIS

In this paper, we assume the following.

- Each source and destination has access to infinite energy, but the intermediate communication nodes are powered by finite energy sources only.
- Each node has a single radio interface, and a node cannot transmit and receive at the same time.
- Data flows according to a *fluid model*.
- Sources have infinite backlogs.
- Propagation delay is negligible.
- Nodes are static.

We represent the network as a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ with multiple sources given by $S_1, S_2, \ldots, S_K$, multiple destinations by $D_1, D_2, \ldots, D_K$ where $S_i, D_i \in \mathcal{N}, 1 \leq i \leq K$. Let $N = |\mathcal{N}|$, $L = |\mathcal{L}|$. Let $w_1, w_2, \ldots, w_K$ be the weights associated with $S_1, S_2, \ldots, S_K$, where, $\sum_{i=1}^{K} w_i = 1$. The weight assigned to a source reflects its priority. Let $E_i$ denote the energy available with node $i$ (in Joules), $\gamma_t$ the energy consumed for transmitting a data bit (Joules/bit), $\gamma_r$ be the energy consumed for receiving a data bit (in Joules/bit), irrespective of the node chosen.

Network partition time, denoted by $\widehat{T}$, is defined as the instant when the *first* source-destination pair disconnects (it

is possible that several sources are disconnected from their respective destinations at this time). We consider the network to be *partitioned* because there is at least one source that is unable to reach its destination.

In a wireless network, links that interfere with one another cannot be activated simultaneously. To address link interference issues, the notions of *Link Contention Graph* and *Maximal Independent Sets* have been introduced [4]. In the LCG, each vertex represents a *link*, and there is an edge between two vertices if the corresponding links interfere. A maximal subset of non-adjacent nodes in the LCG defines a MIS. Evidently, the links in a MIS can be activated simultaneously because they do not interfere.

A *schedule* of wireless link activation can be viewed as a sequence of MIS-es that are activated in sequence. Typically, a periodic sequence of MIS-es is used.

### A. Scheduling of wireless links

Let the bit rate supported by link $l$ be denoted by $C^{(l)}$, $1 \leq l \leq L$. Let $M_1, M_2, \ldots, M_W$ denote the various MIS-es for the given graph, and let a periodic schedule be given. Let $a_i$ denote the fraction (of the period of the schedule) for which the $i^{\text{th}}$ MIS is *on*. A link $l \in \mathcal{L}$ can be present in any of the MIS-es (not necessarily disjoint). The fraction of time for which link $l$ is active is obtained by

$$\nu_l = \sum_{i | l \in M_i} a_i$$

The equivalent link capacity for link $l$ is given by,

$$C_l = \nu_l \times C^{(l)}$$

As the equivalent link capacity $C_l$ is obtained by taking into account the fraction of time for which link is active, we can substitute this link by an equivalent *wired* link of capacity $C_l$ that is active all the time. Evidently, the bits transported by the link over the schedule period remains the same, no matter which view is adopted. This observation forms the basis underlying our approach of constructing an *equivalent wired network*.

Let $\mathbf{C}$ be the capacity vector of size $L$, the $l_{th}$ entry of which represents the effective capacity of the link $l$ for the specified schedule. We represent an independent set $M_j$ by a column vector $\mathbf{r}_j$; the element $r_l = C^{(l)}$ if $l \in M$, and 0 otherwise. Thus, we can write the vector $\mathbf{C}$ as,

$$\mathbf{C} = \sum_{j=1}^{j=W} a_j \mathbf{r}_j$$

### B. Multi-commodity Flow Problem

*The Linear programming Problem Formulation:* The network topology can be represented by a $N \times L$ node-link incidence matrix $\mathbf{A}$, with the entries $A_{nl}$, $n \in \mathcal{N}$, $l \in \mathcal{L}$ being "1" if $l$ originates at $n$, "−1" if $l$ terminates at $n$ and "0" otherwise. Set of end-to-end multi-hop flows constitutes the network traffic where each flow has a source and destination. Flow traffic is routed by the network along one or multiple

paths from source to destination. For each flow, we denote by $x^i$ the amount of flow (measured in bit/s) injected into the network per unit of time by the $i^{th}$ $S - D$ pair, $x$ denotes the amount of flow injected into the network due to all $S - D$ pairs. $y_l$ is the amount of flow traversing link $l$ per unit of time. Let $y_l^i$ denote the flow through link $l$ lying in the $S_i - D_i$ path. Hence, $x = (x^i)$, $\forall i \in [1, 2..., K]$ and $y_l = (y_l^i)_{l \in \mathcal{L}}$, $\forall i \in [1, 2..., K]$ are the flow rate vector and flow link rate vector, respectively. Unless otherwise stated, we will assume vectors are always column vectors. For a vector $z$, $z^T$ denotes transpose of $z$.

- **Flow Constraint**

Assuming lossless transmission, the flow conservation law implies that for $n \in \mathcal{N}$ :

$$\begin{bmatrix} \\ A_{nl} \\ \\ \end{bmatrix}_{N \times L} \times \begin{bmatrix} : & & : \\ y_l^1 & .. & y_l^K \\ : & & : \end{bmatrix}_{L \times K} = \begin{bmatrix} x^1 \\ : & ... \\ -x^1 \end{bmatrix}_{N \times K}$$

and can be compactly written as

$$\mathbf{A}\mathbf{y}^i = \mathbf{u}^i, \; \forall i \in [1, 2, ....K]$$

where $\mathbf{u}^i = (u_n^i)$, $n \in \mathcal{N}$, and $u_n^i$ denotes the amount of flow injected (removed) to (from) the network at node $n$, i.e., $u_n^i = x^i$ if $n = S_i$, $u_n^i = -x^i$ if $n = D_i$ and $u_n^i = 0$ otherwise, $\forall i \in [1, 2, .....K]$.

- **Energy Expenditure Constraint**

The amount of data transmitted and received by any node is limited by the maximum allowable energy available *i.e.*, the initial nodal energy. Let $\widehat{\mathbf{A}}$ denote the node-link incidence matrix $A_{nl}$ where all the "−1"s are replaced by $\gamma_r$ and all the "+1"s are replaced by $\gamma_t$. Recalling the definition of the NPT $\widehat{T}$, we have:

$$\begin{bmatrix} \\ \widehat{A}_{nl} \\ \\ \end{bmatrix} \times \begin{bmatrix} : & : & : \\ y_l^1 & .. & y_l^K \\ : & : & : \end{bmatrix} \times \begin{bmatrix} 1 \\ : \\ 1 \end{bmatrix} \times \widehat{T} \leq \begin{bmatrix} E_1 \\ : \\ E_N \end{bmatrix}$$

Or

$$\widehat{\mathbf{A}} \times \mathbf{y}^i \times \mathbf{1} \times \widehat{T} \leq \mathbf{E}, \; \forall i \in [1, 2, ....K]$$

where $\mathbf{E}$ is $N \times 1$ vector representing the energy available with each node in network.

- **Capacity Constraints**

The capacity of a link limits the aggregate bit rate that it can carry. We have:

$$\begin{bmatrix} : & : & : \\ y_l^1 & .. & y_l^K \\ : & : & : \end{bmatrix} \times \begin{bmatrix} 1 \\ : \\ 1 \end{bmatrix}_{K \times 1} \leq \begin{bmatrix} C_1 \\ : \\ C_L \end{bmatrix}_{L \times 1}$$

Compactly,

$$\sum_{i=1}^{K} y_l^i \leq C_l, \; \forall l \in \mathcal{L}$$

- **Problem Formulation**

Our aim is to maximize the (weighted) aggregate bits carried till NPT. Let $w_i$, $1 \leq i \leq K$, represent the weights associated with the $K$ source-destination pairs; the weights reflect the "importance" of each source-destination pair. Then the problem can be stated as:

**Problem P*:**

$$max \sum_{i=1}^{K} w_i x^i \widehat{T}$$

$$s.\,t.: \ \mathbf{A}\mathbf{y}^i = \mathbf{u}^i, \ \forall i \in [1, 2, ....K]$$

$$\widehat{\mathbf{A}} \times \mathbf{y}^i \times \mathbf{1} \times \widehat{T} \leq \mathbf{E}, \ \forall i \in [1, 2, ....K]$$

$$\sum_{i=1}^{K} y_l^i \leq C_l, \ \forall l \in \mathcal{L}$$

$$y_l^i \geq 0, \ \forall l \in \mathcal{L}$$

$$x^i \geq 0, \ \forall i \in [1, 2, ......K]$$

$$\widehat{T} \geq 0$$

The formulation above is *not* a linear program owing to the presence of the product of unknowns $x^i$, $\widehat{T}$ in the objective function. However, we can convert this problem to a Linear Program in terms of the new variables $(x^{(i)}\widehat{T})$, $1 \leq i \leq K$, $(y_l^i \widehat{T})$, $1 \leq i \leq K$, $1 \leq l \leq L$, and $\widehat{T}$, with suitable modifications of two of the constraints:

**Problem MCF:**

$$max \sum_{i=1}^{K} w_i (x^i \widehat{T})$$

$$s.t.: \ \mathbf{A}(\mathbf{y}^i \widehat{T}) = (\mathbf{u}^i \widehat{T}), \ \forall i \in [1, 2, ....K]$$

$$\widehat{\mathbf{A}}(\mathbf{y}^i \widehat{T}) \times \mathbf{1} \leq \mathbf{E}, \ \forall i \in [1, 2, ....K]$$

$$(\sum_{i=1}^{K} y_l^i \widehat{T}) \leq (C_l \widehat{T}), \forall l \in \mathcal{L}$$

$$y_l^i \widehat{T} \geq 0, \ \forall l \in \mathcal{L}$$

$$(x^i \widehat{T}) \geq 0, \forall i \in [1, 2, ......K]$$

$$\widehat{T} \geq 0$$

**Lemma 1.** *The optimal objective function values in **Problem P*** and **Problem MCF** are equal.*

*Proof:* Let $\widehat{T}^*$, $x^{*,i}$, $1 \leq i \leq K$, $y_l^{*,i}$, $1 \leq i \leq K$, $1 \leq l \leq L$, represent the optimal solution to **Problem P***. We generate the following point which is feasible for **Problem MCF**: $\widehat{T} = \widehat{T}^*$, $(\tilde{x}^i \widehat{T}) = x^{*,i}\widehat{T}^*$, $1 \leq i \leq K$, and $(\tilde{y}_l^i \widehat{T}) = y_l^{*,i}\widehat{T}^*$, $1 \leq i \leq K$, $1 \leq l \leq L$. Clearly, the point $\left(\widehat{T}, (\tilde{x}^i \widehat{T}), (\tilde{y}_l^i \widehat{T})\right)$ is feasible for **Problem MCF** as the point $\left(\widehat{T}^*, x^{*,i}, y_l^{*,i}\right)$ is feasible for **Problem P***, and the objective function for

**Problem MCF** at $\left(\widehat{T}, (\tilde{x}^i \widehat{T}), (\tilde{y}_l^i \widehat{T})\right)$ is equal to the *optimal* objective function for **Problem P***. Therefore,

<div align="center">

Optimal objective in **Problem MCF** $\geq$

Optimal objective in **Problem P***

</div>

Similarly, starting from the optimal solution $\left(\widehat{T}^*, (\tilde{x}^i \widehat{T})^*, (\tilde{y}_l^i \widehat{T})^*\right)$ to the **Problem MCF**, we can generate a feasible point for the **Problem P***, and the objective function value of **Problem P*** at *this* point will equal the *optimal* objective function value of **Problem MCF**. This implies that

<div align="center">

Optimal objective in **Problem P*** $\geq$

Optimal objective in **Problem MCF**

</div>

From these two inequalities, the claim follows. □

## EXAMPLE 1

In Fig. 1, nodes $N1$, $N2$, $N3$ have energy 60, 80, 80 $J$, respectively. Energy consumed per bit of transmitted and received data are denoted by $\gamma_t = 10^{-4} \ J/bit$ and $\gamma_r = 10^{-6} \ J/bit$, respectively. The raw capacity of each wireless link is taken to be $C = 8 \times 10^4 \ bits/sec = 80 \ Kbps$.

The wireless link interference model is as follows. Two links $L_1$ and $L_2$ interfere with each other if either node of $L_1$ is within two hops of one of the nodes of $L_2$. With this model, the MIS-s are: $\{(1,7),(3,8),(1,8),(3,7),(2),(5),(4),(6)\}$. The wired equivalent link capacities [4] are:
$C_1 = C_3 = C_7 = C_8 = (2/8) \times C = 20Kbps$
$C_2 = C_4 = C_5 = C_6 = (1/8) \times C = 10Kbps$
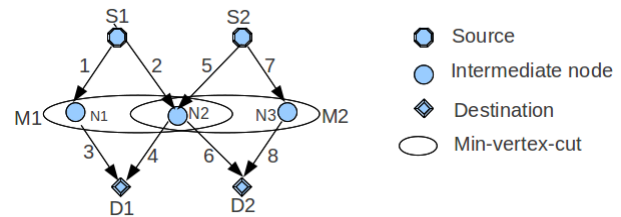


Fig. 1. An example showing 2-$Ss'$ transmitting to their respective $Ds'$. The paths $S_1 - N_1 - D_1$, $S_1 - N_2 - D_1$ for $S_1 - D_1$ and $S_2 - N_2 - D_2$, $S_2 - N_3 - D_2$ are the Node-disjoint-paths for $S_2 - D_2$, respectively. The links are marked from 1 to 8.

The solution of **Problem MCF** yields a weighted aggregate bits transported till NPT of $\mathcal{F}_{MCF}^1 = 16.71C \ bits$ for $w_1 = 0.25$, $w_2 = 0.75$, and $\mathcal{F}_{MCF}^2 = 13.62C \ bits$ for $w_1 = 0.5$, $w_2 = 0.5$.

It is interesting to note that the solution obtained by solving **Problem MCF** exactly determines the solution for **Problem P***. Consider the equal weight case for **Problem P***, the optimal solution for the link flow vector is $\begin{bmatrix} 14289.52 & 9870.35 & 14289.52 & 9870.35 \\ 9182.33 & 9182.335 & 19052.68 & 19052.68 \end{bmatrix}$ bits/sec. The data injected into the network by the two sources', flow

rate vector, is $\begin{bmatrix} 2415.98 & 2823.50 \end{bmatrix}$ bits/sec. The disconnection time $\widehat{T}$ is 41.57 sec.

- Clearly, all the link-flows are less than the link-capacity which indicates that for maximizing aggregate bits transported, a greedy strategy is not required.
- **Problem MCF** insists on maintaining the flow rate vector constant over time, leading to an optimal solution where all source-destination pairs disconnect at the same time. So, even though our formulation considered the time till at least one $S - D$ pair is disconnected, the MCF formulation provides a solution where all sources get disconnected at the same time. This is proved in the following Lemma.

**Lemma 2.** *The optimal solution to* **Problem MCF** *yields a Network Partition Time* $\widehat{\widehat{T}}^{*}$ *at which* **all** *source-destination pairs are disconnected.*

*Proof:* Suppose that the optimal solution to **Problem MCF** has been found, and the NPT $\widehat{\widehat{T}}^{*}$ is such that at least one source-destination pair is not disconnected. Without loss of generality, we assume that there is just one source-destination pair that is not disconnected; in case there is more than one, the argument below can be repeated.

Consider the source that is not disconnected from its destination. There must be at least one path from this source to its destination such that all nodes on this path have positive residual energy. Therefore, this path can sustain data transfer for a longer duration $\widehat{T}_{1}$ (say), where $\frac{\widehat{T}_{1}}{\widehat{\widehat{T}}^{*}} =: \alpha > 1$. Using $\widehat{T}_{1}$, we can generate a solution to **Problem MCF** at which the objective function increases strictly. To do this, we consider a solution where all other source rates are decreased to $x^{*,i}/\alpha$, which allows path lifetimes to increase to $\alpha\widehat{\widehat{T}}^{*} = \widehat{T}_{1}$. This means that the aggregate bits transported by these sources till time $\widehat{T}_{1}$ remains the same as before. The source rate for the pair that is not disconnected is maintained at the same level as before. Then, because $\widehat{T}_{1} > \widehat{\widehat{T}}^{*}$, we conclude that the aggregate bits transported till $\widehat{T}_{1}$ is strictly greater than that transported till $\widehat{\widehat{T}}^{*}$. This is a contradiction, and hence the claim follows. $\square$

## IV. ROUTING

In the previous section, we presented an approach to obtain the maximum (weighted) aggregate bits transported, before all sources lose connectivity to their respective destinations. In this section, we turn to the practical issue of routing. Our objective is to examine the routing strategy based on Node Disjoint Paths (proposed in the literature) in terms of the same criterion, *viz.,* aggregate bits transported before disconnection.

### Node-Disjoint-Path Routing

NDP routing is discussed prominently in the literature [18] [19] [20] [23] [24] [25]. However, many papers use limited number of NDPs for routing; we consider routing through the maximum possible number of NDPs.

*1) Finding the maximal NDP set for routing:* Our approach is based on Menger's Theorem[26], which states that "The *min-cut* for a $S-D$ pair equals the *maximum number of NDP.*" The Node-Disjoint-Paths for each $S - D$ pair is constructed such that:

1) Each path contains exactly *one* node belonging to the min-vertex cut for the $S - D$ pair.
2) The total number of paths formed for a $S-D$ pair equals the cardinality of the min-vertex cut set for that $S - D$ pair.

*Remark:* In case of overlapping min-vertex cut-sets for the $S - D$ pairs, the total number of NDP might exceed the total cardinality of min-vertex cut-set for the graph.

*2) To calculate the Total Data Transferred:* After having identified a NDP set for a source-destination pair, our approach is to consider each of the node disjoint paths, and obtain the data transferred through it. We assume that *sources are greedy*, in the sense that they transmit at the maximum rate possible, subject to the constraints that link capacities are finite and have to be *shared* among all flows that pass through those links.

Focusing on a specific path in the NDP path set, our approach is to find the lifetime of each node on the path. The node lifetime is determined by the node's available energy, and the total data rate through it. The smallest node lifetime is the path lifetime. Finally, we calculate the total number of bits transported from each source that uses the path to the corresponding destination. Iterating over paths, we obtain the weighted aggregate bits transported before disconnection.

## EXAMPLE 2

Referring to Fig 1, let $T_{N1}$, $T_{N2}$ and $T_{N3}$ denote the lifetimes of nodes $N1$, $N2$ and $N3$, respectively. Using the equivalent wired link capacity values obtained earlier (just above Fig 1), and recalling that $\gamma_t = 10^{-4}$ and $\gamma_r = 10^{-6}$, we have, $T_{N1} = 60/((10^{-4}+10^{-6}) \times (2 \times 10^4) \times 1) = 29.71\ sec$, $T_{N2} = 80/((10^{-4} + 10^{-6}) \times (1 \times 10^4) \times 2) = 39.61\ sec$, $T_{N3} = 80/((10^{-4} + 10^{-6}) \times (2 \times 10^4) \times 1) = 39.61\ sec$. Let the weights given to $S1$ be $w_1 = 0.25$, to $S2$ be $w_2 = 0.75$. Data transferred across $S_1 - D_1$ is $(29.7 \times (C/4) + 39.6 \times (C/8)) = 12.38C$. For $S_2 - D_2$ it is $(39.6 \times (C/8) + 39.6 \times (C/4)) = 14.85C$. Hence the total data transferred is given by $\mathcal{F}_{NDP}^{1} = (0.25 \times 12.38 + 0.75 \times 14.85) \times C = 14.23C$. Now, let weights be $w_1 = 0.5$, $w_2 = 0.5$. Total data transferred is given by $\mathcal{F}_{NDP}^{2} = (0.5 \times (12.38 + 14.85) \times C) = 13.62C$.

*Remark:* The data obtained for this example when both the sources have equal weights are same for both the methods, but discrepancy in results exist when the weights are unequal.

## V. RESULTS

Following are the results obtained for $\gamma = \gamma_t = \gamma_r = 10^{-2}$ Joules/bit, $C = 10^2$ Bits/sec for given number of nodes

(maximum till 40) and edges (maximum till three times number of nodes) where the graphs are formed randomly. The energy allotted to nodes is chosen randomly from values 1 to 100. The weights given to sources are all equal.

After 50 runs in MATLAB, the average percentage deviation in aggregate bits transported based on the NDP approach as compared to the MCF approach turned out to be (approximately) the following:
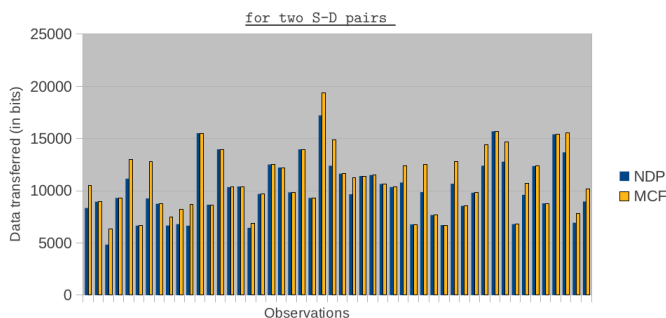
1) *7.5% for two S-D pairs*



Fig. 2.    Performance Comparison of NDP vs MCF for multiple nodes and two S-D pairs.
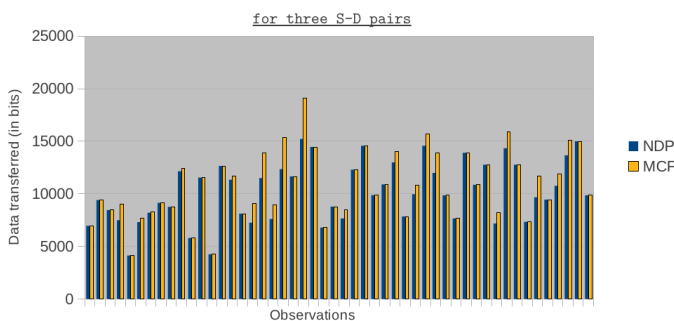
2) *4.5% for three S-D pairs*



Fig. 3.    Performance Comparison of NDP vs MCF for multiple nodes and three S-D pairs
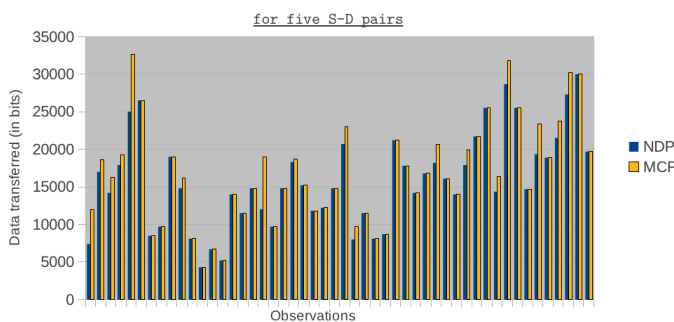
3) *5% for five S-D pairs*



Fig. 4.    Performance Comparison of NDP vs MCF for multiple nodes and five S-D pairs.
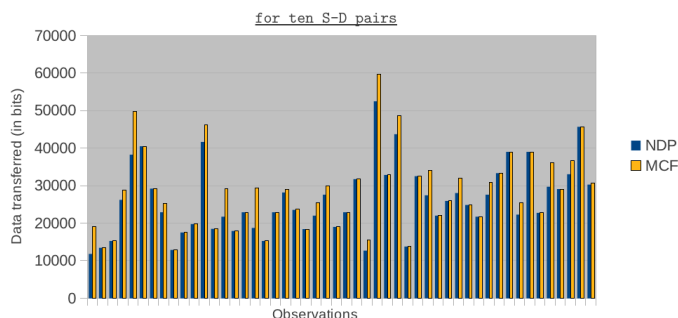
4) *6% for ten S-D pairs*



Fig. 5.    Performance Comparison of NDP vs MCF for multiple nodes and ten S-D pairs.

It was noted that the deviation in results decreases with larger number of observations. Thus, the performance of the NDP approach is close to the optimal that can be achieved.

## VI.  CONCLUSION AND FUTURE WORK

We considered a scenario where the communication nodes in a sensor network had limited amounts of available energy, and the objective was to maximize the aggregate bits transported from sources to respective destinations before network partition due to node deaths. The metric "aggregate bits transported" results from considering *both* network throughput and network lifetime, and captures the useful information that a sensor network can provide; by itself, neither factor can provide this. We formulated an optimization problem that turned out to be non-linear; however, we showed that it could be converted to a Linear Program, the solution of which yielded the optimal objective value. Next, we compared the performance of a practical routing strategy, based on Node Disjoint Paths (NDPs), with the ideal obtained from the Linear Program, and found that the aggregate bits transported by NDP-based routing strategy was within 7.5% of the optimal, indicating that it is a promising strategy for our metric.

As part of future work, we will develop a framework for evaluating routing and MAC protocols in sensor networks, leveraging the approach given in this paper. The framework will allow an *analytical comparison* between candidate routing and MAC protocol combinations. Each MAC protocol will lead to a specific equivalent wired network model, resulting from MAC characteristics like transmit powers, link speeds (depending on the MAC technology), duty cycle, etc. The equivalent network will allow a study of routing protocols in terms of the aggregate bits transported.

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