On the Lifetime Extension of Energy-Efficient Multihop Broadcast Networks

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Abstract - In this paper, we address the problem of energy efficient multicast routing in wireless Mobile Adhoc NETwork (MANET). It is a challenging environment because every node operates on limited battery resources and multihop routing paths are used over a constantly changing network environment due to node mobility. We define the network lifetime as duration of time until first node failure due to battery energy exhaustion and show that the network lifetime for a multicast session can be significantly extended by additionally considering residual battery energy as a parameter in cost metric function for constructing a power efficient routing tree. We also present a post-sweeping algorithm that further reduces the energy expenditure compared to the random sweeping proposed previously [1]. Simulation results are presented which supports our approach.

I. INTRODUCTION

The military mobile network consisting of soldiers on the move, emergency search and rescue, dynamic coalitions and ubiquitous computing are some of the applications of wireless mobile ad-hoc networking that make extensive use of multicast/broadcast communications [4]. A salient feature of many of these networks is the use of microprocessor embedded, energy constrained devices that have the capability to perform advanced computations. Due to the battery energy constraint of these devices, it is essential to develop computational/networking algorithms and protocols that are optimized for energy consumption under each clock cycle. The battery energy of a transmitting node can be depleted due to: (a) processing at the node, (b) transmission attenuation due to path loss, and (c) the need to maintain the transmission above a certain threshold due to signal interference. Designing energy-efficient unicast algorithms and protocols has been an active area of research [4]-[6].

Recent study in [2] presents extensive comparison on the performance of different multicast routing protocols suitable for MANET and concludes that ODMRP which combines on-demand and mesh-based approach has the best performance when energy is not a constraint. Since the ODMRP uses a flooding scheme to set up the routes, the use of it in the case of energy-constrained networks will lead to rapid battery exhaustion. Hence, new approaches that incorporate energy constraints and increase lifetime of the node battery are needed.

A series of recent papers [1] and [3] present an approach that tries to develop energy-efficient broadcast routing trees. They presented a tree construction that makes use of needed power expenditure by the nodes in developing an energy-efficient routing solution.

II. BACKGROUND

In this paper we present an approach that tries to construct a dynamic and energy-efficient broadcast tree using a weighted cost function that includes residual battery level. In order to do so, we make use of a recently proposed power-efficient broadcast tree construction algorithm as a building block and construct our cost functions. Based on these newly proposed cost functions, we derive solutions that lead to significant improvements in extending the lifetime of the network. We now review the broadcast advantage property of the omni-directional antenna in wireless medium [1].

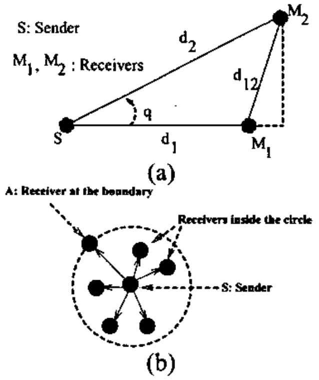

Figure 1: (a) Geometric construct of a sender S and receivers M_1 and M_2 (b) Wireless broadcast advantage

A Wireless Broadcast Advantage

Fig.1(a) shows a single sender S with receivers M_1 and M_2 at distances d_1 and d_2, respectively, from the sender. We assume that $d_2 > d_1$ and the received power at a node varies as $d_i^{-\alpha}$ $(i = 1, 2)$ where α is the path loss (attenuation) factor satisfying $(2 \leq \alpha \leq 4)$. Hence, the transmission power required to reach a node at a distance d_i is proportional to d_i^{α} assuming the proportionality constant is 1. Fig.1(b) shows the broadcast nature of the wireless medium for omni-directional antenna in which a unit of message sent to receiver A at the boundary of the circle reaches every node within the circle for "free." In order to transmit an identical message to nodes M_1 and M_2, S can use two unicast transmissions with individual power d_1^{α} and d_2^{α}. This leads to the total expenditure of $(d_1^{\alpha} + d_2^{\alpha})$ by S. However, the energy expenditure can be reduced by taking advantage of the fact that the wireless medium is naturally "broadcast." Under this assumption, the sender has to choose

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between the following two strategies: (a) if $d_2^\alpha > d_1^\alpha + d_{12}^\alpha$, transmit to M_1 and let M_1 transmit to M_2, (b) otherwise, transmit to M_2 directly (M_1 will automatically receive it due to wireless broadcast advantage since $d_2 > d_1$). Hence, joint consideration of the effect of transmission and routing leads to savings in battery energy.

For an arbitrary network topology, the construction of minimum total power routing tree does not have a known efficient algorithm. It can be shown that the construction of minimum total power broadcast tree is not the same as the minimum weight spanning tree problem (MST) [7]. However, there is a sub-optimal solution due to [1] called *Broadcast Incremental Power* (BIP) algorithm that uses greedy approach to construct a tree. We describe it below.

B Description of the BIP Algorithm

BIP Algorithm: a heuristic greedy algorithm

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Input: given an undirected weighted graph $G(N, A)$, where $N$: set of nodes, $A$: set of edges
Initialization: set $T := \{S\}$ where $S$ is the source node of multicast session. Set $P(i) := 0$ for all $1 \le i \le |N|$ where $P(i)$ is the transmission power of node $i$.
Procedure:
while $|T| \neq |N|$
        do find an edge $(i, j) \in T \times (N - T)$ such that incremental power $\Delta P_{ij} = d_{ij}^\alpha - P(i)$ is minimum.
        add node $j$ to $T$, i.e., $T := T \cup \{j\}$.
        set $P(i) := P(i) + \Delta P_{ij}$.
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The BIP algorithm described above uses the broadcast advantage property while trying to construct a power efficient tree. As with many other heuristic greedy algorithms, this algorithm is not globally optimal for producing a multicast tree with minimum total power expenditure. As noted earlier, currently there is no known globally optimal algorithm (except exhaustive search) that is also computationally efficient. Moreover, due to the distributed nature of adhoc network, the source node may not have global knowledge of network topology in advance without which tree construction is impossible.

III. PROPOSED APPROACH FOR NETWORK LIFETIME EXTENSION

We define the *network lifetime* as the duration of time until the first node in a network fails due to the battery exhaustion. In case all the nodes have identical initial energy level, the node that spends the battery power at the highest rate will exhaust its battery first. If we want to extend the lifetime of the network, it is critical to incorporate the residual battery energy into route selection criteria. We note that, although the BIP algorithm produces a power efficient multicast routing tree for a single transmission of a packet (which is efficient for a short term period), it does not deal with maximization of the lifetime (which is a long term period) of a network. Moreover, in a more realistic scenario, the tree structure derived by BIP can not be maintained for a long period of time due to the node mobility and eventually it has to be updated either periodically or when the network configuration changes. We can now reformulate the BIP as an optimization problem.

A Reformulation of the cost metric for power efficient multicast tree (BIP):

Finding a multicast routing tree T_{BIP} with BIP algorithm can be reformulated as a corresponding optimization problem as follows:

$$T_{BIP} \cong \arg\min_{T\in G(N,A)} \sum_{(i,j)\in T} \Delta P_{ij} \qquad (1)$$

over all possible trees T that are subgraph of $G(N,A)$ and all edges (i, j) contained in the tree T. Note here that equation (1) is written as an approximation and not as an equality, because the BIP algorithm is not guaranteed to produce optimal solution. The objective here is to minimize the total incremental transmission power which is defined as a summation of all non-zero incremental powers. As a result, a tree T_{BIP} is heuristically constructed in a greedy fashion over all possible trees T. By the nature of greedy algorithm, the produced output is not guaranteed to be a global minimum. However, since the BIP algorithm is designed at least to try to solve the above optimization problem, similar notation will be adopted throughout this section for notational simplicity. The exact meaning of it should be interpreted as a recursive greedy formulation explained in section II.B.

B Proposed cost metric for extending network lifetime using Weighted BIP (WBIP):

We noted that the original BIP algorithm in equation (1) does not incorporate the residual battery energy into route tree selection. In order to incorporate the residual battery energy into the cost function, we multiply additional weighting factor to the incremental power ΔP_{ij} before constructing the total weighted cost function. The weighing function denoted by W_i for node i is a time dependent function. The corresponding optimal tree is given by

$$T_{WBIP} \cong \arg\min_{T\in G(N,A)} \sum_{(i,j)\in T} W_i \Delta P_{ij} \qquad (2)$$

$$W_i = E_{total} \Big/ \left(E_{total} - \sum_{k=0}^{n} E_{ik}\right) \qquad (3)$$

and E_{total} is the initial battery energy of node i, and E_{ik} represents the amount of energy consumed at node i during the k-th update interval (Δt). Therefore, the denominator of W_i represents the remaining battery energy of node i at time $t = n\,\Delta t$. Notice here that the weighting factor W_i is initially set to unity (i.e., BIP) and as time progresses and more energy is consumed, W_i is monotonically increasing (i.e., $W_i \ge 1$). The cost metric $C_{ij} \equiv W_i\,\Delta P_{ij}$ (WBIP) includes both node-based cost and link-based cost. The battery energy which is a characteristic of a node is represented in W_i. The more a node has remaining energy, the less W_i is and, therefore, there is a greater chance for this node with large battery capacity to be included in the route. The reason for W_i being called node-

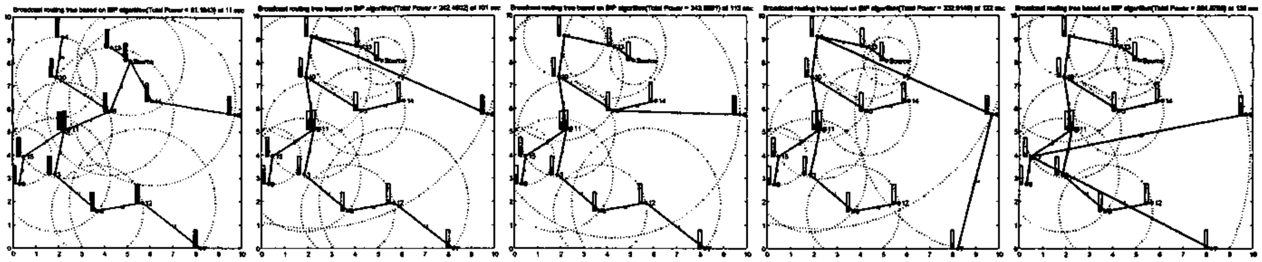

(a) (b) (c) (d) (e)

Figure 2: Routing tree oscillation problem for a sample network configuration with 15 nodes

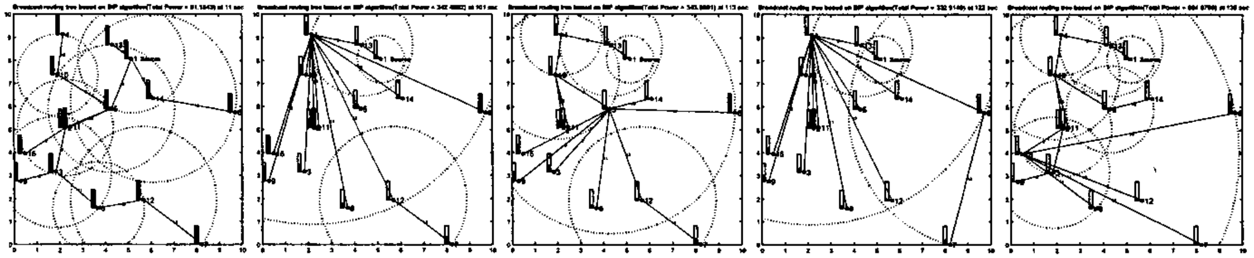

(a) (b) (c) (d) (e)

Figure 3: Same network configuration as Fig.2 with post sweeping applied routing tree at every update interval

based cost is that this value is equally weighted to all links to which this node is incident and it will be avoided if this weighting factor is large. On the other hand, ΔP_{ij} is a link-based cost because different values are assigned for each link (i, j).

C Using Post Sweeping for Lifetime Extension: Weighted BIP with Post Sweeping (WBIPSW)

As mentioned before, the BIP algorithm does not produce a tree with globally minimal total power. The power expenditure in the resulting suboptimal tree can sometimes be further reduced by making use of *post sweep procedure* described in [1] which is an heuristic optimization technique. A sweeping algorithm essentially removes redundant hops and thus saves power expenditure independent of the specific routing algorithm. In [1], the post sweep procedure is explained using an example and nodes are examined in the order of ascending node ID number. This is in essence the same as applying post sweep procedure randomly to each node since the nodes are randomly located in a network. Our approach is based on the observation that since the underlying data structure is a tree, a more systematic approach can be developed independent of the ordering of the node ID.

In our implementation, we choose a top-down approach instead of random post sweeping, which is described in the following paragraph. Our top-down approach has additional advantage over random post sweeping because, the number of hop count to the nodes affected by post sweeping always decreases. In terms of conventional performance measure of routing protocols (e.g., shortest path routing), this corresponds to better delay characteristic because the node can be reached with fewer hops. Although a top-down approach is presented in this paper, similarly, a bottom-up approach can be used.

At first, sweeping from the source node (the root node of a multicasting tree) down to every node in the sublevels is applied. Note that by the way the BIP tree is constructed, every child node is always within the transmission range of its parent node. If there is a node, which is within the transmission range of source node, this node is directly connected to the source node. The operation is repeated from the source node down to every leaf node.

Fig.2 presents a 10×10 grid with $\alpha = 2$ for 15 nodes using WBIP algorithm described in section III.B. In Fig.2, we present the WBIP based routing tree solution at different time instances. Every node is represented with a point and the solid lines correspond to the established links in the spanning tree. The circles with dashed-line represents the transmission ranges of the nodes located at the center of each circle. The remaining battery level is represented with a shaded rectangle in Fig.2. The oscillations of the route paths for different time instances are visually clear if we consider the lower half of the network. It can be observed that the battery depletion is evenly distributed among the nodes by the choice of this metric, which justifies the metric (2) for lifetime extension. However, the oscillations have an adverse effect on designing a routing protocol because it can result in out of order packet arrivals.

The effect of applying our implementation of the post sweep procedure (WBIPSW) can be readily seen from Fig.3. In Fig.3, the same network configuration as Fig.2 is used but, at each update interval, post sweeping is applied. In the case of WBIP, the weights generated by the residual battery energy increases as time progresses and hence the value of the cost function also increases with time. This in turn leads to an increase in the total power required to construct trees using WBIP. Thus the effect of post sweeping on energy saving can be significant as time progresses.

IV. SIMULATION RESULTS

In this section, simulation was performed with a simplified network model according to the different metrics BIP, WBIP and WBIPSW presented in the previous section. Within a 10×10 square grid region, network configurations are randomly generated with uniform distribution of nodes and a multicast tree based on BIP algorithm is constructed from the source node. Path loss exponents of α = 2, 3 and 4 are separately considered in the simulation. To isolate the effect of each metric, all the generated nodes are assumed to be in the multicast group (broadcasting). Initial energy of the battery in each node is assumed to be 1000 units and the broadcast tree is updated at every specified update interval (Δt). Constant bit rate (CBR) traffic model is used to broadcast from the source node to all the destination nodes. The simulation results are for the static network topology without node mobility and no restriction on the maximum available transmission power $P_{\max} = \infty$ is imposed. At every update interval, the amount of energy consumed during the time period is subtracted from the corresponding remaining energy level. Also, energy consumption by transmission power only is assumed because reception or idle period power is relatively small compared to transmission power.

In Fig.4, the network lifetime of the original BIP algorithm, the metric WBIP (2), and the metric WBIPSW for further optimizing total transmission power with sweeping are compared for different values of α = 2, 3 and 4 and for update interval of Δt = 1 second with 20 nodes. In each case, 100 different network topologies are generated and network lifetime was calculated. The same random seeds are used for each metric for valid comparison.

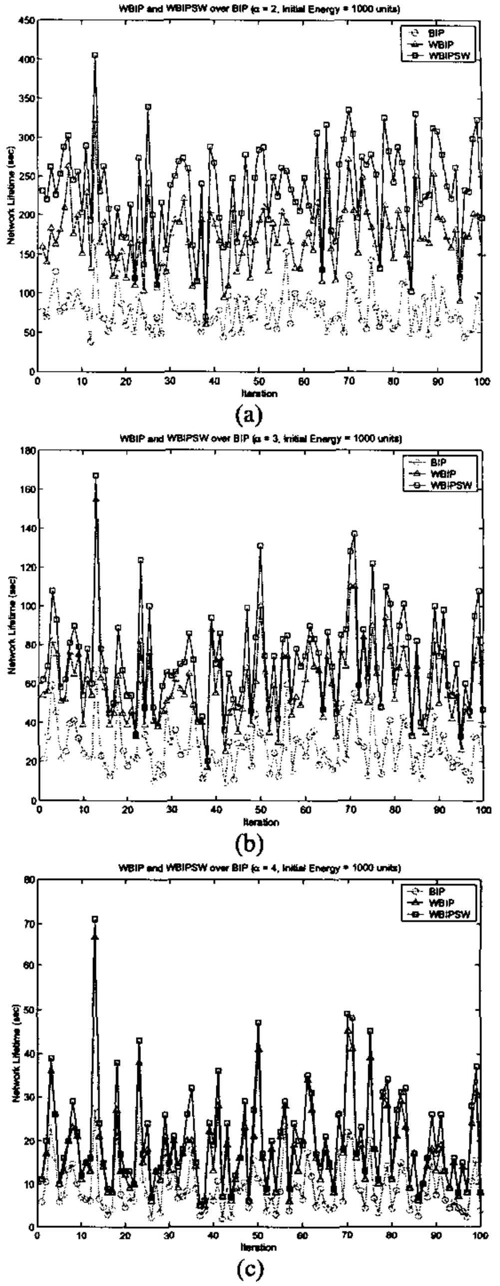
Path Loss	BIP	WBIP	Gain (%)	WBIPSW	Gain (%)
α=2	78.1/24.8	170.8/43.5	118.7	232.8/60.5	198.1
α=3	27.7/12.8	58.9/20.9	112.6	72.0/25.6	160.0
α=4	9.2/5.7	17.7/10.1	92.4	20.3/11.6	120.7

Table 1: Mean and standard deviation of network lifetime for 100 network instances: 20 nodes, Δt = 1(sec) where gain ≡ (a–b)/a×100% and a is either lifetime of WBIP/WBIPSW and b is lifetime of BIP

Path Loss	BIP	WBIP	Gain (%)	WBIPSW	Gain (%)
α =2	78.1/24.8	689.2/178.8	782.5	933.2/246.6	1094.9
α =3	27.7/12.8	246.9/84.0	791.3	296.4/102.8	970.4
α =4	9.2/5.7	76.4/41.1	730.4	85.8/46.3	832.6

Table 2: Mean and standard deviation of network lifetime for 100 network instances: 20 nodes, Δt = 0.25(sec)

Table 1 and 2 summarize the performance in terms of network lifetime, in which the mean value, standard deviation (STD), and gain in terms of the percentage increase in network lifetime from BIP to WBIP and WBIPSW is shown. As propagation constant α becomes larger, the lifetime of the network is shortened significantly because power expenditure is much larger (i.e., $d_{ij}^4 >> d_{ij}^2$). However, standard deviation becomes smaller as α becomes larger. We can observe from Table 1 that, by using the WBIP and WBIPSW, the network lifetime is roughly prolonged by a factor of two (~100%) and three (~200%) compared to BIP, respectively, when Δt = 1 and α = 2 which is a significant enhancement assuming the given fixed amount of initial battery energy.



(a)

(b)

(c)

Figure 4: Network lifetime of BIP,WBIP and WBIPSW for (a) α=2 (b) α=3 (c) α=4 (100 network instances)

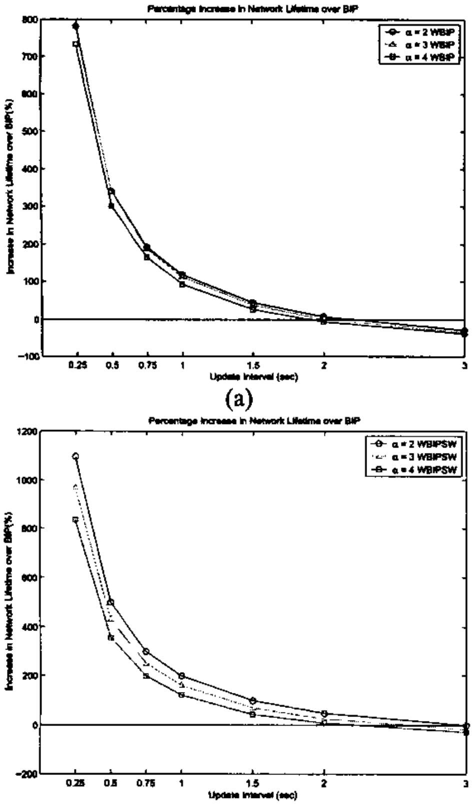


Figure 5: (a) Percentage increase in mean network lifetime of WBIP vs. route update interval: 20 nodes (b) Percentage increase in mean network lifetime of WBIPSW vs. route update interval: 20 nodes

The dependence of percentage increase in average network lifetime of WBIP on the update interval for 100 instances with 20 nodes is shown in Fig.5(a) for α = 2, 3 and 4. For update interval of 1 second ($\Delta t = 1$), there is about 100% increase in lifetime which is consistent with the result in Table 1. If the tree is updated every 250 millisecond ($\Delta t = 0.25$), the lifetime can be prolonged by 750-800% over BIP. It is evident from Fig.5(a) that if the tree is updated more frequently, the more lifetime is prolonged. However, if $\Delta t > 2$, it begins to be shorter than BIP.

The same behavior occurs with WBIPSW where further increases in network lifetime over WBIP are visible in Fig.5(b). More update rate translates to higher control overhead. Therefore the control overhead should be further analyzed so that we can choose proper update interval in protocol specification.

The dependence of lifetime on the node density (number of nodes per 10×10 region) with $\Delta t = 1$ second is presented in Fig.6(a and b). For α = 2, lifetime increases almost linearly to the node density whereas the increase is more steep for α = 3 and 4. In summary, our results show that there are essential trade-offs between network lifetime, oscillations and update intervals and therefore proper values should be chosen for protocol design.

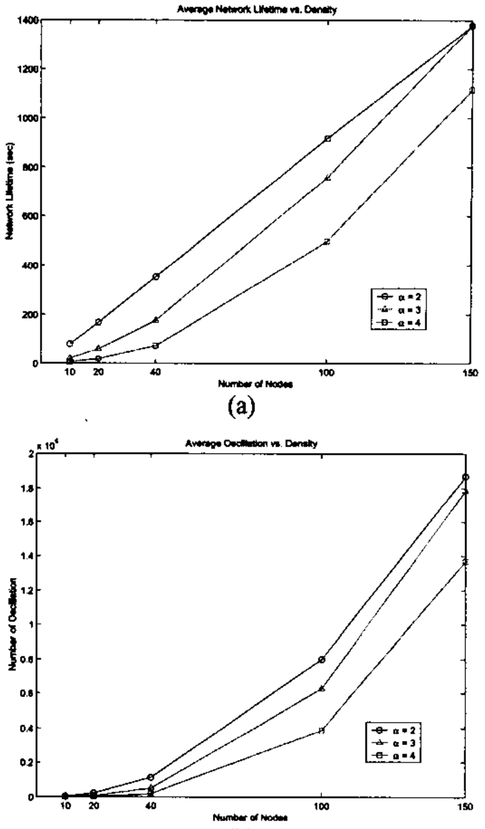


Figure 6: (a) Network lifetime vs. node density: $\Delta t = 1$ sec (b) Routing path oscillation vs. node density: $\Delta t = 1$

V. CONCLUSIONS

We presented an approach that enabled us to extend network lifetime by a factor of two compared to the seminal results in [1], if the tree is updated every unit of time. We noted that as the update time interval reduces, the lifetime of the network increases. However, this comes at a cost of additional computations. We showed that using a systematic post-sweeping algorithm leads to further reduction in overall energy expenditure of the network. Using our scheme of post sweeping, we were able to increase the lifetime of the network by a factor of three compared to results in [1]. We note that (though the specific numerical values of the gains may vary,) the gain due to the proposed approaches is not restricted to the topologies presented.

Current trends of research in multicast routing protocols seem to be leaning toward mesh-based approach mainly because of superior performance of ODMRP. However, our results suggest that the tree-based protocols should also be further pursued because of its energy efficiency. Our future work involves finding a spanning tree with globally minimum total power, better metrics for lifetime and stability, and protocol design of this algorithm to conduct packet level simulation including node mobility. We intend to investigate the possibility of a linear programming formulation of this algorithm.

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