Power aware routing algorithms for wireless sensor networks

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***Abstract*— Recently there have been numerous research results in the area of power efficiency in ad hoc and wireless sensor networks. This paper discusses the effect of power efficient routing algorithms on the lifetime of multihop wireless sensor networks (WSNs). The WSNs considered are special cases of mobile ad hoc networks (MANETs); in particular, we assume that all data and control traffic in the WSN is flowing between the sensor nodes and the base station. This assumption results in a considerably simpler problem and solution than for the more general MANETs. We calculate analytically lifetime bounds of the WSN under specific routing algorithms. The main result of the paper is that, for WSNs, the choice of the routing algorithm has almost no consequence to the lifetime of the network. This result, as well as being obviously useful, is somewhat surprising since this is not true of general MANETs.**

I. Introduction

Recent technological advances in the areas of microcontroller architectures, sensors and low power wireless transceivers have made it possible to deploy large wireless sensor networks (WSNs).

Thousands of wireless sensor nodes are expected to autoconfigure and operate for extended periods of time (days or months, possibly years) without physical human intervention. In many systems it can be expensive or impossible to replace the batteries. For such WSNs, the power management strategies play a vital role in extending the useful lifetime of the network.

The power management problem for WSNs has been studied intensively. Various approaches for reducing the energy expenditure have been presented in literature; several papers minimize the transmitter power (a significant energy drain for WSN nodes) while maintaining connectivity. Several routing protocols [1]–[7] showed significant improvements in the network lifetime for ad hoc networks (MANETs) by choosing routes that avoid nodes with low battery and balancing the traffic load. Approaches at the medium access control (MAC) layer are geared towards reducing idle listening power and decreasing the number of collisions. Application layer approaches show dramatic energy savings for several classes of applications. Other papers show that cross-layer approaches may also be very effective at conserving energy. In this paper we focus on routing strategies that maximize the lifetime of the WSN (as defined in Section II-A).

Several strategies are commonly employed for power aware routing in WSNs [1]:

- Minimizing the energy consumed for each message [2], [4]. This metric might unnecessarily overload some nodes causing them to die prematurely.
- Minimizing the variance in the power level of each node [8]. This is based on the premise that it is useless to have battery power remaining at some nodes while others exhaust their battery, since all nodes are deemed to be equally important.
- Minimizing the cost/packet ratio [1]. In this approach, different costs can be assigned to different links, for example, incorporating the discharge curve of the battery, and thus postponing the moment of network partition.
- Minimizing the maximum energy drain of any

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node [3], [9]. The basis of this approach is that the network utility is first impacted when the first node exhausts its battery, and thus it is necessary to minimize the battery consumption at this node.

The above approaches focus on different metrics of energy efficiency. A common characteristic of these metrics is that they can lead to a disconnected network with a high residual power: once the critical nodes of the network have depleted their batteries, the network is essentially dead. Indeed we show that under our assumptions this is inevitable. For a practical sensing application, the network can be considered to have stopped working when it fails to deliver the sensed readings from a bulk of the sensors, and the important metric is the time when this occurs. In what follows, we will therefore use the network lifetime as our main performance measure, which we define in the next section.

While all the above approaches provide benefits in different classes of MANETs, the special case of WSNs merit closer evaluation since they are practically an important class of MANETs. Generally, the problem of computing the optimal lifetime of the MANETs is known to be hard due to node mobility. As a special case of MANETs, the WSNs are (in most sensing applications) stationary and have a base station sink, where all data traffic ends. In this paper, we will derive bounds on the lifetime of WSNs. We show that the two characteristics mentioned above play a crucial role in these considerations. Somewhat surprisingly, we are able to show that network behavior under these conditions is quite specific, the maximum benefit obtainable from the batteries is very predictable, and achievable by rather simple routing strategies.

II. Definitions, Notations, and Assumptions

In this section, we define the lifetime of the network (the metric for determining the optimality of routing algorithms). We also present the assumptions and notations used in the following sections.

A. Definitions

Definition *1:* The lifetime of the set $\mathcal{N}$ of sensor nodes is the duration

$$L_{\mathcal{N}} = t_e - t_s, \tag{1}$$

where t_s is the start time of the network and t_e is the time when no sensor nodes in the set $\mathcal{N}$ can send data to the base station.

The lifetime of the network L is the lifetime of the set of all its initial nodes.

B. Assumptions

We believe that the following assumptions apply to a large class of sensor network implementations and applications.

We assume that:

- A-1 all network nodes are stationary,
- A-2 all sensed data is sent to the base station (i.e. no filtering or other in-network processing is performed),
- A-3 all network nodes generate packets periodically with a common constant period,
- A-4 the transmission range and transmission power is constant for all transmissions from all nodes,
- A-5 all nodes have the same initial battery level,
- A-6 there are more nodes in tier $i+1$ than in tier i except for the last tier of nodes. (In terms of the notation we introduce in section II-C $N_{i+1} \geq N_i$, $1 \leq i \leq H-2$.) If this assumption holds at deployment time, it will continue to hold for the lifetime of the network since the inner tiers carry more traffic that the outer tiers and, thus, more nodes die in the inner tiers than in the outer tiers.
- A-7 the traffic forwarding load from nodes which are more than i hops from the base station is equally shared by all nodes which are i hops from the base station.

Of the above, the first two are the crucial ones we mentioned before. The next two assumptions merely represent a realistic case, and also simplify what follows, but do not reduce the scope of our results. A-5 also represents a quite realistic condition; the removal or relaxation of this assumption is not considered within the scope of this paper. A-6 is satisfied for most reasonable distribution of sensor nodes, for example approximately uniform distribution over a large area. The assumption of a uniform distribution is stronger than A-6 and is not needed for this paper. The main purpose of the minimal assumption A-6 is to eliminate pathological cases where the WSN becomes prematurely disconnected due to a bottleneck in the topology. Finally, A-7 is made for explanatory purposes and later we examine the consequences of removing this assumption.

C. Model and Notations

We model the power consumption P of a wireless node as:

$$P = P_a T + P_b, \tag{2}$$

where T is the number of flows transmitted by the node (comprising its own sensed data and data forwarded on behalf of other nodes), P_a is the power consumption used to forward the data in each flow, and P_b is the power consumption independent of the forwarded traffic. A sensor node that consumes the same power independent of the number of flows forwarded is likely a wasteful node. A power efficient sensor network has a very small P_b (mainly due to routing overhead, synchronization and other middleware services), practically all its power being expended in useful sensing and forwarding of information. In WSNs the traffic from the base station to the sensor nodes (queries, control information, etc.) is usually broadcast and hence contributes to P_b rather than to P_a. The choice of the MAC layer clearly influences the power efficiency of the network – power efficient MAC layers result in reduced P_a and P_b. Beyond the particular values of P_a and P_b, the choice of the MAC layer is not relevant for the reminder of this paper.

Regardless of its value, for our purposes, P_b does not play a role in the contribution of routing to the network lifetime L: simply by offsetting the initial battery level by a constant quantity ($P_b L$) we can compute the same lifetime L by using a simplified model for the power consumption of a node:

$$P = P_a T. \tag{3}$$

We will use the following notation:

- β is the energy spent to transmit one packet once.
- p is the number of packets generated by each node in every second (thus, the energy spent every second by each node to generate or forward one flow is βp).
- b is the initial battery level of every node (as discussed only the battery expended for forwarding and sending its own data is relevant for the network lifetime).
- H is the maximum number of hops between the base station and any of the wireless nodes in the WSN.
- $\mathcal{N}$ is the set of all sensor nodes.
- $\mathcal{N}_i$ is the set of sensor nodes that are at a minimum of i hops away from the base station. We also call this set of nodes the i^{th} *tier* of nodes. For example, the first tier of nodes consists of the nodes that can directly reach the base station. With our assumptions, initially all nodes of in $\mathcal{N}_i$ will also be exactly i hops from the base station; however, as nodes in $\mathcal{N}_{i-1}$ die, some nodes in $\mathcal{N}_i$ may require more than i hops to reach the base station, and become part of the set $\mathcal{N}_{i+1}$. *However, note that nodes in* $\mathcal{N}_1$ *never migrate to other tiers.*
- N is the total number of sensor nodes; $N = |\mathcal{N}|$.
- N_i is the number of nodes in tier i; $N_i = |\mathcal{N}_i|$.
- $T_i^r(n)$ is the number of packets transmitted by node $n \in \mathcal{N}_i$ using the routing algorithm r.
- L^r is the lifetime of the network when using routing algorithm r
- L_i^r is the lifetime of the nodes of $\mathcal{N}_i$ when using routing algorithm r.
- $\mathcal{R}$ is the set of all *minimum hop* routing algorithms able to find a path between each sensor node and the base station if such a path exists. Usually, each node in the set $\mathcal{N}_i$ has multiple shortest hop neighbors in the set $\mathcal{N}_{i-1}$; The choice of one of these neighbors (e.g. randomly, or based on the residual power) differentiates among the algorithms in $\mathcal{R}$.

III. THE EFFECT OF THE ROUTING ALGORITHMS ON THE LIFETIME OF THE WSN

When the traffic pattern in a network is such that all nodes transmit to an *egress* node such as a base station, the few nodes that can reach the base station directly will be responsible for the highest amount of traffic forwarding. We have examined this phenomenon in detail in [10], below we present the result that is relevant to us in the current context. Then we use this result to obtain lower and upper bounds for the lifetime of the network as a function of the routing protocol.

Lemma *1:* For any routing algorithm $r \in \mathcal{R}$, the lifetime of the nodes in $\mathcal{N}_1$ is equal to the lifetime of the nodes in other tiers ($\mathcal{N}_i$, $i > 1$). In other words, $L_1^r = L_i^r$ for all i and r such that $1 < i \leq H$ and $r \in \mathcal{R}$.

Proof: For all $r \in \mathcal{R}$ and $i > 1$,

$$\sum_{n \in \mathcal{N}_1} T_1^r(n) > \sum_{n \in \mathcal{N}_i} T_i^r(n) \tag{4}$$

because there are no loops in the paths through the nodes in tier i and, hence, the traffic in the first tier of nodes *includes* the traffic from any other tier (and adds its own traffic). Using either (2) or (3) this implies that the power consumption of nodes in the first tier is higher than that of the nodes in any other tier. Since all nodes have the same initial battery size (assumption A-5) and there are more nodes in tier i than in tier 1 (assumption A-6), the nodes in the first tier will deplete their battery strictly sooner than the nodes in any other tier. However, as soon as the first tier of nodes depletes its batteries, the entire network becomes disconnected (and by the definition of the lifetime in Section II-A all tiers reach their lifetimes). ■

Theorem *2:* For a WSN satisfying all assumptions in Section II-B and using a routing algorithm $r \in \mathcal{R}$ the lifetime of the network is

$$L_{\min} = \frac{N_1 b}{N \beta p}. \tag{5}$$

Proof: According to Lemma 1, the lifetime of the network is determined by the lifetime of the first tier of nodes. Considering assumption A-7, every node in the first tier will expend the battery at the same (constant - assumption A-3) rate. Further, each flow originating from outside of tier 1 is forwarded by exactly one first tier node: since tier 1 nodes are the only nodes that can transmit directly to the base station. Each first tier node also originates exactly one flow of its own. Finally, considering that all nodes have the same initial battery (assumption A-5), all nodes in the first tier will deplete their battery *at the same time*. The moment when the first (and last) battery is depleted coincides with the time of the death of the network. Thus, the battery expended on the first tier of nodes is used to forward data for all nodes in the network for the duration of the networks' lifetime:

$$N_1 b = L_{\min} N \beta p. \tag{6}$$

■

The above is valid if all nodes are alive until the lifetime expires, as will happen if the load balancing assumption A-7 strictly holds. However, this will not hold in practice because the node positions may have some asymmetry. We next examine the consequence of removing the assumption. To distinguish, we shall refer to the ideal routing situation where the assumption A-7 is perfectly met as *Load Balanced Shortest Path First* (LBSPF).

We focus on the first tier, since we know the lifetime is defined by these nodes. If assumption A-7 is not satisfied in the first tier, then all nodes of the first tier will not die at the same time. The lifetime of the network will be defined by the first tier node which dies last. However, before this time, the number of first tier nodes still alive has declined slowly. The number of nodes that remain alive in the first tier at any given time affects the total traffic generated by the first tier itself. Initially, the total battery amount of first tier nodes is $N_1 b$. For each period, the first tier consumes an energy equal to $N_{alive} \beta p$, where N_{alive} is the number of active nodes in the network. A routing algorithm can maximize the lifetime of the network if it can reduce N_{alive} as soon as possible. A practical way to quickly reduce the number of nodes that are alive is to overburden a node until its battery is depleted. Thus, the routing algorithm should select a node x_1 in the first tier and route *all* flows through node x_1 until it depletes its battery. After node x_1 dies, another node from the first tier, x_2, is selected to carry all the network flows, and so on until the last node in the first tier dies (at which time the network becomes disconnected). We shall refer to this rather curious routing approach as *Bottleneck Routing* (BR). While BR does not belong in the set $\mathcal{R}$ (not all nodes in tier 2 may be able to reach x_1 in one hop), it represents the extreme limit of unbalanced routing protocols in $\mathcal{R}$. Thus all protocols in $\mathcal{R}$ will result in a network lifetime bounded by those achieved by LBSPF and BR, from below and above respectively.

In LBSPF, the base station will receive readings from all nodes for the entire lifetime. This is no longer true for BR, some nodes will die and stop reporting before lifetime expires. While this may be a problem from the sensing application's perspective, we show below that it improves the lifetime of the network as we defined it earlier.

Theorem *3:* If we remove assumption A-7, the maximum lifetime of a WSN using a routing algorithm $r \in R$ is bounded by $L < L_{max}$, where

$$L_{\max} = \frac{b}{\beta p}\left[1 - \left(1 - \frac{1}{N - N_1 + 1}\right)^{N_1}\right] \quad (7)$$

Proof:

As discussed above, the lifetime is composed of different periods when the different nodes of the first tier will take turns forwarding all traffic from outside the first tier. To compute the lifetime of the network we simply add the times it takes for all nodes in the first tier $x_1, x_2, \ldots, x_{n_1}$ to die:

- node x_1 will carry the flows on behalf of $N - N_1$ nodes and its own flow. Thus it will die after $t_1 = \frac{b}{(N-N_1+1)\beta p}$.
- node x_2 will carry only one flow for time t_1 and then the same number of flows as node x_1, and hence will die after t_2 seconds after the death of x_1: $t_2 = \frac{b - t_1\beta p}{(N-N_1+1)\beta p}$.

  ⋮
- node x_{N_1} will die t_{N_1} seconds after node x_{N_1-1} died, where $t_{N_1} = \frac{b - \sum_{i=1}^{N_1-1} t_i \beta p}{(N-N_1+1)\beta p}$.

Thus,

$$L_{\max} = \sum_{i=1}^{N_1} t_i. \quad (8)$$

Equation (8) can be further manipulated by noticing that $t_i = t_1(1 - \frac{1}{N-N_1+1})^{i-1}$ for all i such that $2 \leq i \leq N_1$. Then (7) follows immediately as the sum of a geometric distribution.

■

Comments:

- LBSPF and BR are the two extreme approaches to routing in WSNs. LBSPF ensures that the time of the death of the first node is postponed as much as possible. On the other hand, BR postpones the time of the disconnection of the network as much as possible. Any minimum hop routing will result in routes that will fall between these two extremes, hence so will the lifetimes.
- Figure 1 depicts the difference in the network lifetimes of the two approaches as a function of the total number of nodes N over the number of nodes in the first tier N_1. For this figure N_1 was kept constant at 100 nodes while N increased from 200 nodes to 2500 nodes. It is interesting to see that the difference between the two extremes becomes very small as total number of nodes becomes large in comparison to the number of nodes in tier 1.
- Bottleneck Routing maximizes the lifetime of the network at the expense of purposely depleting some of the nodes relatively early. For most applications it is unlikely that this is desired, especially since, for large networks, the savings in the lifetime are insignificant (Fig. 1). This observation makes the definition of *optimal* WSN routing protocols that use only the lifetime as an optimization criteria questionable.

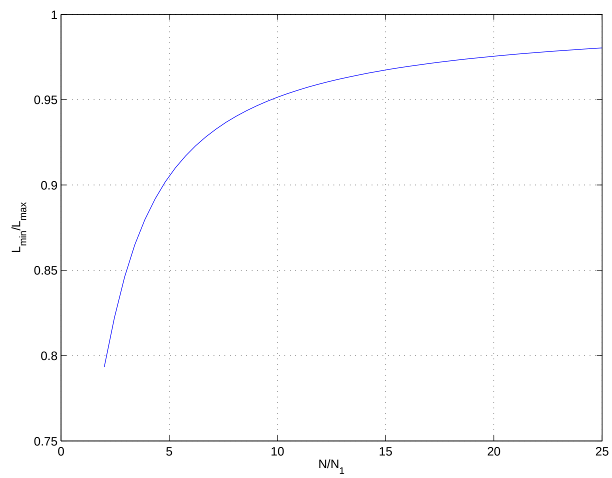

Fig. 1. Lifetime ratios using LBSPF and BSPF as a function of the ratio between the total number of nodes and the nodes in tier one.

It is clear that for all possible routing algorithms in $\mathcal{R}$ the lifetime L of the network falls somewhere between the two extremes: $L_{\min} \leq L < L_{\max}$. Moreover, the two extremes are very close to each other especially for large networks. Therefore it can be claimed that the choice of the routing protocol does not make a significant difference in the lifetime of the network. For example, in a uniformly distributed WSN with five tiers the difference between the two lifetimes is less than 2%.

It is likely that a simple protocol will perform just as well as a more complex protocol. The only major differentiation between different routing protocols is in their overhead (included in P_b in (2)).

IV. Simulation Results

To validate the results in Section III we simulated a WSN of variable size with two routing algorithms.

We have implemented two versions of Shortest Path First (SPF) algorithms to compare the lifetime of WSN using these algorithms with the theoretical limit:

MSPF The algorithm selects among the neighbors with the same number of minimum hops to the base station the one with the largest remaining power. Essentially this algorithm behaves very similar to Load Balancing SPF ensuring that all nodes in the first tier die at (almost) the same time.

RSPF The algorithm selects randomly among the neighbors with the same number of minimum hops to the base station.

We reroute (choose new routes for all nodes) periodically (every one time unit) or whenever a node dies.

We fixed the node density at $(0.01 nodes/m^2)$ and the transmission radius of the nodes $(30m)$. The transmission of the data generated by a node each time unit costs one unit of energy. The nodes initially have 1000 units of energy. All simulations were repeated thirty times with different random seeds; in what follows, the average of these results is presented.

Figures 2 and 3 depict the variation of the network lifetime with the network size (constant density) for uniform (we used a rectangular grid) and random placement respectively. The lifetimes of network using the two versions of SPF algorithms are very close together and between the theoretical values given by (5) and (7). The lifetime are so close that they are hard to tell apart from each other. There is also no significant difference between the strictly uniform and the random placements beyond the significant variation introduced by the random initial topology. Figure 3 also depicts the 95% confidence interval corresponding to the average lifetimes. The lifetime of the network decreases as the number of sensor nodes increases: a fixed number of tier one nodes carry increasingly more packets and, hence, naturally die sooner.

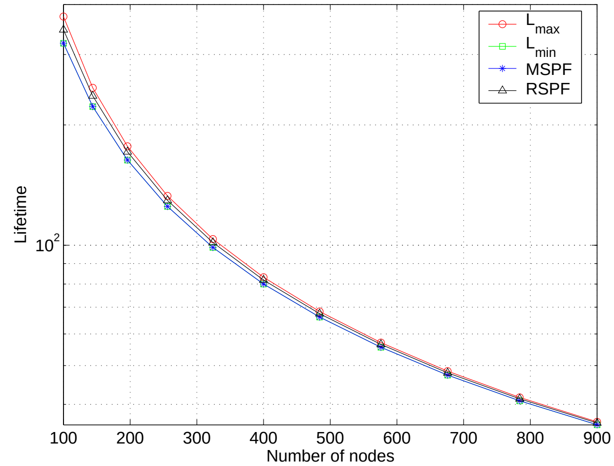

Fig. 2. Variation of the lifetime of the network for a rectangular grid placement as a function of the networks size

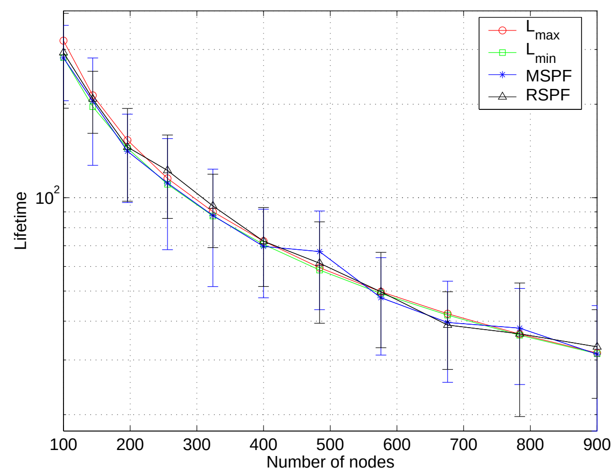

Fig. 3. Variation of the lifetime of the network for random placement as a function of the networks size

Figures 4 and 5 show the moment of death of each node in the first tier of the network. For the two limits corresponding to $L_{\min}$ and $L_{\max}$ we depicted the times when first tier nodes are expected to die following the LBSPF and BR algorithms. For this simulation we used $N = 400$ nodes in an area $190m \times 190m$. MSPF for the grid network works as expected: practically all nodes of the networks are alive for the entire lifetime of the network. For the random placement scenario, MSPF works reasonably well, but less so than in the case of the uniform grid. The main reason behind this

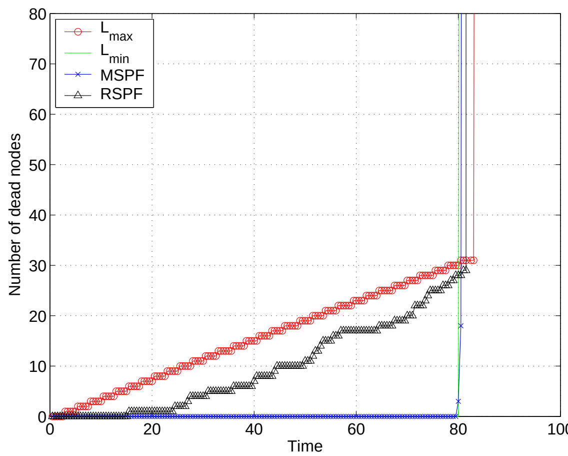

Fig. 4. Time of death for each node for various routing strategies for an uniform rectangular grid placement.

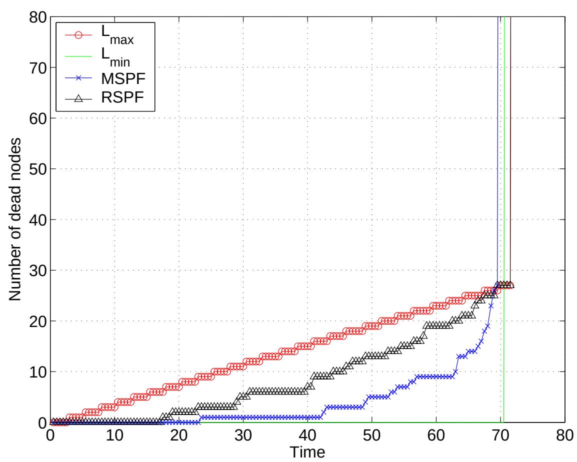

Fig. 5. Time of death for each node for various routing strategies for a random placement.

behavior is that in the case of random placement there might not be possible to balance the load, and inevitably some nodes will die sooner than others. The number of disconnected nodes spikes abruptly when the network becomes disconnected, i.e. when the network reached its lifetime. As expected, for both placements, the lifetime of RSPF is slightly larger than for MSPF at the expense of the early deaths of some tier one nodes.

V. Conclusion

In this paper we presented an analysis of the lifetime of wireless sensor networks that employ periodic sensing. Lower and upper bounds on the network lifetime are derived, and corresponding routing algorithms leading to these bounds are presented. For large sensor networks the upper and the lower bounds on the network lifetime are relatively close (less than a few percents), leading thus to the conclusion that for such sensor networks the choice of the routing protocol is largely irrelevant for maximizing the network lifetime, as long as some form of shortest paths are followed. Simulations are used to validate the theoretical results.

While the set $\mathcal{R}$ may appear to be rather restrictive, in reality our results are likely to continue to hold for many sensible routing approaches. We are currently working on developing descriptions of such routing families, and on extending the concept of network lifetime.

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