Connectionless Probabilistic (CoP) routing: an efficient protocol for Mobile Wireless Ad-Hoc Sensor Networks

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Abstract

We present a protocol that manages Wireless Ad-Hoc Sensor Networks in several scenarios including large scale, high density and high mobility deployments. One of the main applications is to communicate important information from inaccessible areas by spreading just "enough" mobile sensors which must self-configure and assemble. According to our protocol, Connectionless Probabilistic *(CoP) routing, the information is routed in a multi-hop, cluster level fashion by enabling each sensor to make individual decisions regarding its mode of operation. The aim is to prolong the network's lifetime by minimizing the energy spent for each communication. CoP is capable of addressing high mobility requirements as it is completely independent of any kind of topological knowledge and control messages. We show by extended experiments that CoP performs very well in terms of consumed energy by comparing it to a standard directed flooding and a greedy forwarding protocol.*

1 Introduction

Recent developments in wireless, mobile communications combined with the constant advancements in electronics that enable the integration of complex components into smaller devices, have contributed to the emergence of a new class of wireless ad-hoc networks: Sensor Networks. Typically a sensor board consists of a number of sensors of different modalities which, when combined with a microprocessor and a low-power radio transceiver, forms a smart network-enabled node. A sensor network may deploy a huge number of nodes depending on the nature of the application. Such applications include medical services, battlefield operations, crisis response, disaster relief, environmental monitoring, premises surveillance, robotics and more.

In a mobile, ad-hoc, wireless field, a network consisting of homogeneous nodes of equal capabilities is assumed. Typically a distinguished node, referred in the literature as the *sink*, is responsible for gathering data collected by the other nodes and forwarding it to the external, fixed infrastructure for further processing. Such a node can be assumed non-mobile since it is the one connecting the sensor field with the external infrastructure. According to this description, a sensor network has obvious similarities with a traditional ad-hoc network but also vital differences (see [1] for a survey). For the rest of the paper we will use the abbreviation MANETs when referring to traditional mobile, ad-hoc networks and WSNs to denote mobile, ad-hoc, sensor networks.

According to the most prominent power attenuation model [2, 3, 4], when a node s transmits to a node r with power P_s, the power at the point where r lies will be: $P_r = \frac{P_s}{\|s,r\|^{\kappa}}$ where $\|s,r\|$ is the Euclidean distance between the source and the receiving node, and k is the distance power gradient. In the real world, it holds that $2 \leq k \leq 6$ according to the topology of the space. As energy consumption is proportional to the square distance between the communicating nodes for the two dimensional Euclidean space, multihop forwarding is preferred over direct transmission (like traditional MANETs). Therefore data is routed back to the sink through a series of links between neighboring nodes that may have no knowledge of the future or even current topology of the network due to its vast number of nodes and their high mobility.

2 Our Contribution

In this paper we present a new protocol to perform communications between a set of sensors and a fixed infrastructure (the sink) in a mobile sensor environment. The model we assume constitutes of a uniformly distributed set of sensors inside a given flat surface (hence $\kappa = 2$). The only thing that each sensor needs to know in order to participate in the protocol is its own location and the location of the sink. According to the model we adopt, a communication session begins when a sensor needs to inform the sink about some collected information of interest, according to its application. Such a message will have to be transmitted to a "centralized storage device" (the fixed infrastructure) in order to be processed with all the other information coming from other sensors spread on the WSN field. Such a device is part of the outside fixed infrastructure and then each sensor knows its location. Since computing operations is cheaper than transmissions (see for instance [5, 6]), aggregating information is desired.

Location-aware routing protocols for ad-hoc networks typically assume some kind of awareness of a greater topology amongst the distributed sensors. Very usually this means that in order to make local decisions, the nodes are required to know their neighbors' positions as well as from their own. This is achieved by exchanging control messages that consume considerable amounts of energy in large, densely deployed, mobile networks. The key idea of the CoP protocol is that the saving of energy is achieved not only by choosing an appropriate path between source and destination pairs but also by eliminating all the transmissions usually needed by other protocols to choose the next hop node or just to communicate the positions of the nodes. Furthermore, since we assume mobility in our model, the determination of static paths or the knowledge of the neighbors' locations could be useless in many cases where real-time connectionless communication is required.

In CoP, clustering methods are also used to reduce the number of needed hops to establish the required communication session and hence reduce the average routing time. To this end, we propose a two-level communication model (easily extendable) in which each node is a self-candidate to be either a normal sensor or a clusterhead. A further advantage for our protocol is that it copes very well with mobility since the status of each sensor changes according to its actual position and hence the nodes participating in the communications can constantly change hence sharing the energy consumption.

Messages are routed on a virtual infrastructure that we represent as a grid covering the sensed area. Since the sensors are randomly spread on the area of interest, we fix a distortion parameter that we called ds as the maximum distance from a virtual grid node where the real sensor has to reside in order to self-candidate itself and become a clusterhead, see Figure 1. Roughly speaking this means all sensors in the fixed range of a grid node "believe" they are grid nodes. All the other remaining sensors are then associated to some grid node just by the minimum distance.

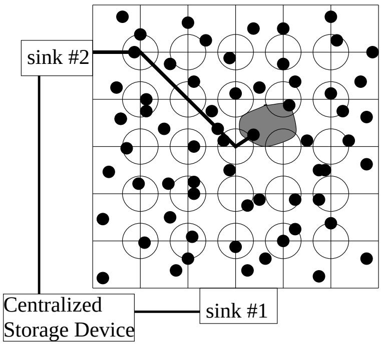

Figure 1: Multihop routing from the area of interest (shaded area) to the sink in a sensors field using the virtual grid. The empty circles represent the area associated to each virtual grid node. Every node inside such an area is a clusterhead.

3 The Model

For the sake of simplicity, let A be a square area of sides' size l in which the sensors are distributed. We define a grid of unit u over it, the intersections of which represent the location of the probable clusterheads. As we said we try to build a sort of virtual infrastructure in order to compute the desired communications. Since we assume that each sensor knows its own location, it can decide by itself whether it is or not a clusterhead. Moreover, according to the density of the sensors with respect to A, we can evaluate the probability $p_{ds}(i,j)$ for which a sensor is at distance ds from the virtual grid intersection of coordinates $g_{i,j}$. We can then imagine a circular area of radius ds associated with each intersection in such a way that a sensor decides to be a clusterhead if and only if it is inside such an area.

More precisely, from the "balls into bins" theory (see for instance [7]), we know that throwing randomly n points in a unit square, the probability that no nodes are inside a circle of diameter dr with

$$dr = 2ds = \sqrt{\frac{c \log n}{n}} \tag{1}$$

is given by $(1 - \frac{dr^2}{4})^n \leq e^{-\frac{ndr^2}{4}} = n^{-\frac{c}{4}}$ for a given constant c. Therefore fixing $c > 4$ such a probability is very low. Choosing then an appropriate distortion ds, according to the density of the thrown nodes in the region of interest, we can compute our desired communication without fail with very high probability.

The configuration can easily change with time, according to the degree of the sensors' mobility but each one can decide which is the closest clusterhead-area or if it is a clusterhead itself. Moreover, unless the mobility follows some given pattern, the configuration of the nodes can be assumed to be random at every instant. Furthermore, depending on the nature of the application using the WSN, we can adjust the accuracy of the results returned and the granularity of the sensing by simply enlarging the area associated with each grid point or by simply placing more sensors inside the area of interest. Moreover, this latter modification can be made during the time that the network is in operation in order to prolong its lifetime or increase its accuracy. Another reason that more sensors would be added to the area of interest could be the presence of a new sink added to a new location. In this way the new sensors could decide which is the closest sink and where to transmit data according to their actual position. Notice that all the other "old" sensors will participate as well in this newer topology since the transmitted messages includes the target position. The same technique could be also used to enlarge the area of interest or to join two already existing ones.

If a sensor is a clusterhead, it can transmit the collected information to the next clusterhead-area in order to reach the sink. Clearly the route that is formed will be close to a stair-path over the grid. The transmission power that is needed by each sending node will be at most $(2d+u)^2$ and each sending node can easily compute it by itself. On the other hand, in order to save energy, if it is not too expensive with respect to the chosen grid unit, we can also allow transmissions across the diagonal of a grid box. In this case, the maximum range of a transmission will be $2d + (\sqrt{2})u$.

If a sensor is not a clusterhead, it is inside a cluster and it therefore must transmit its information to the closest clusterhead. Such a communication session could be established in a multihop fashion as well. In this case we can recursively define another grid and perform the same kind of communications. As already mentioned, for the sake of simplicity, we are considering a two level clustering and hence each sensor inside a cluster is a clusterhead of the bottom level 1. Since the transmission power of a node of level 1 is at most $\frac{\sqrt{2}}{2}u + d$ with a very low probability, the clusterheads of level 2 spend more energy compared to the nodes of level 1. Therefore, in order to prolong the lifetime of the entire network, we can assume a sort of rotation, according to the frequency of the communications and the mobility of the nodes. In fact, if the network is characterized by high mobility, then every node frequently changes its status from clusterhead of level 2 to clusterhead of level 1 and vice-versa according to its actual location. Yet another advantage that can be exploited in the CoP protocol lies in the fact that if a node is not a clusterhead, it can switch off its receiver since it will be used for its sensing capabilities alone.

Notice that the choice of a square grid is made in order to simplify the discussion and experiments. In fact, all the previous arguments stand for any kind of virtual grid infrastructure.

4 Connectionless Probabilistic (CoP) routing

In this section we formally describe our protocol as a routing algorithm for each sensor.

Let $\hat{x}$, $\hat{y}$ be the grid constructor vectors on the x and y axis respectively, $\vec{ds}$ be the radius vector defining the association areas around the grid intersections, $\vec{r}_s$, $\vec{r}_d$ and $\vec{r}_c$ be the position of the source, destination and current node c respectively. Let m be the message to be routed, C, $C_{ij} \subset C$ and S be the set of clusterhead nodes, the set of clusterhead nodes associated with grid intersection $g_{i,j}$ and the set of the rest of the nodes respectively.

Next we describe the clusterheads' self-selection and transmission phases. The position of the grid intersection $g_{i,j}$ is $\vec{g}_{ij} = \alpha\hat{x} + \beta\hat{y}$ where $\alpha, \beta \in Z$ and $i, j \in \{1, 2..., \frac{l}{u}\}$.

```
procedure $CoP(ds, \vec{sink})$
Find the actual position $\vec{r}_c$;
Evaluate the closest grid node $\vec{g}_{i,j}$;
if $\vec{r}_c == \vec{g}_{ij} + \vec{\varepsilon}$ for some vector $\vec{\varepsilon}$,
where $\|\vec{\varepsilon}\| \le \|\vec{ds}\|$ then
    STATUS = CLUSTERHEAD; \* $c \in C$
    RECEIVER = ON;
else
    STATUS = ASSOCIATED TO $\vec{g}_{i,j}$; \* $c \in S$
    RECEIVER = OFF;
end if
SENSING;
if SENSING == m || RECEIVE == m then
    Let $s \in \vec{sink}$ be the closest sink;
    TRANSMIT($m, s$);
end if
```

The first operation that each sensor must perform is to discover its actual position. Since equipping all sensors with a GPS receiver is infeasible due to size and energy constraints, this can be achieved by using some service such as the Ad-Hoc Positioning System (APS) [8] or the GPS-less low-cost outdoor localization for very small devices proposed in [9].

Each sensor must then decide itself if it is or not a clusterhead. This decision is made by computing its distance from the virtual infrastructure defined by the grid. In the first case it will be used to perform communications from other close sensors to the direction of the fixed sinks while in the latter its duties will be restricted to sensing. Whenever an information is revealed by the sensing operation or received from another sensor, it is forwarded till the sink by the following procedure of transmission.

```
procedure TRANSMIT($m, sink$)
if $c \in C_{ij}$ and
no node $c' \in C_{ij}$ has transmitted $m$ in the past then
    $c$ transmits $\{m, c, sink\}$ towards intersection in position $\vec{g}_x$ : $\min \|\vec{g}_{pq} - \vec{r}_d\|$, where $\vec{p} = \{i, i \pm 1\}$ and $\vec{q} = \{j \pm 1, j\}$ with radius $r = \|\vec{g_x} - \vec{ds}\|$
else
    Discard $m$;
end if
```

In the transmission phase, the sensor checks if any other sensor has already sent the same message to decide either to send it or just to discard it. As a result of the choice of omnidirectional antennas, a clusterhead may receive messages although it is not in the path from the source to the sink. In this case it will not forward the message.

```
procedure RECEIVE($m, c, sink$)
Add $sink$ to $\vec{sink}$;
Let $c'$ the actual position of the receiver;
if $||c', sink|| < ||c'', sink||$ for every clusterhead $c''$ belonging to one of the 8 grid nodes surrounding $c$ then
    RETURN m;
end if
```

Notice that a node knows whether it is one of the intermediate clusterheads for which the message is destined on its way to the sink. To this aim, in fact, it is sufficient to compute the remaining distance to reach the sink and comparing it with the other 7 possibilities that each time a message has in order to be forwarded (that is the 8 grid nodes surrounding one node). In this way, multiple paths to deliver a same message are avoided.

5 Experiments

In our experiments we consider a two layer network. Regarding mobility, we model random sensor movement. In most applications, random movement can be considered to be the worst case scenario since any knowledge of movement rule, pattern or behavior can be exploited to reduce the communication cost.

We compare CoP to a standard directed flooding protocol and a basic greedy forwarding scheme. We chose these protocols, first because they are both very well known, basic schemes and therefore provide a good reference point for the comparisons. More importantly, they are both based on the assumption that each node knows its position which makes the comparison with CoP completely legitimate.

CoP's virtual infrastructure not only enables the nodes to route messages without exchanging any control packets but also incorporates another important optimization characteristic of the multihop communication model. As showed in [5], direct transmission can be more efficient than multihop communication under specific circumstances concerning the number of intermediate nodes and their distance. This is because the transmitting and receiving devices consume an additional amount of energy which corresponds to the running of their electronic circuits and is independent of the energy spent on the signal's way between them. This factor, which in some cases can dominate the communication, is constantly neglected by many recent protocols.

According to our model, transmitter and receiver electronics consume an equal amount of energy per bit, namely $5nJ/bit$. This implementation choice is in favor of multihop transmission and therefore directed flooding and greedy forwarding algorithms. Notice that the value we use is 10 times smaller than the one used in [5]. The energy to support the signal above some acceptable threshold against power attenuation caused by the distance is just $100pJ/bit/m^2$. By switching off the receivers of all the non-clusterhead nodes, CoP not only provides an aggregation points definition mechanism but also addresses the issue induced by the energy consumption over the hardware. This way, by calibrating the grid's constructor vector in accordance with the nodes' density CoP can provide optimized real-world communication.

We first compare CoP with a location-based directed flooding scheme. According to this algorithm, upon receiving a new message, each node forwards it to its neighbors only if it is closer to the destination than the node from which it received it. In our experiments we always consider the minimum cost of directed flooding obtained by consider the minimum radius for the transmission range. The ds parameter of CoP, instead, is chosen a priori just by applying the Equation 1 of the probability formulation of Section 3.

The second test protocol is a greedy forwarding algorithm according to which, the node that has the message broadcasts a request using some fixed radius. The neighbors that receive this request, respond with a control message that contains their current location. Upon receiving the responds, the sender picks the node that is closer to the sink. It then sends the data message, adjusting its transmission according to the next node's position. Control messages (requests and responds) were set to be of size 40 times smaller than the data messages.

Notice that none of these protocols guarantees delivery of the message to the destination. Trying to tune the involved parameters so as to preserve as much energy as possible can cause the protocols to fail in many cases. Throughout all our experiments, and according to the properties of the different instances, we constantly changed the values of the protocols' parameters (e.g the fixed radius ranges involved in the other two protocols) so that we can achieve the same high probability of delivery at the minimum energy cost for all the protocols.

We conducted experiments, considering a dense $5x5m^2$ sensor field, consisting of 100 up to 1000 nodes. All parameters, including the constant ranges and the energy spent on the transceiver electronics, are tuned in a way that directed flooding and greedy forwarding achieve maximum energy savings for roughly the same delivery probability as CoP. The results of the experiments are illustrated in Figure 2 where the X-axis represents hundreds of nodes and the Y-axis the energy spent on the entire network for the delivery of the message, in nJ. As expected, directed flooding scales extremely poorly for dense environments with respect to CoP but also greedy forwarding.

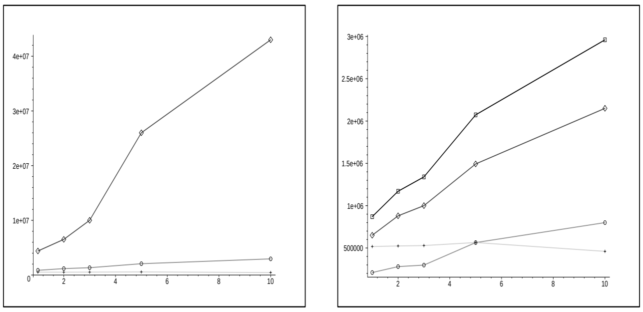

Figure 2: CoP (+) compared with Minimum Directed Flooding (O) and Minimum Greedy Forwarding (◇) (*left figure*) and CoP (+) compared with minimum Greedy Forwarding (□) and its subdivisions into the energy spent effectively for data messages (O) and the energy spent for control messages (◇)(*right figure*).

6 Conclusions

We presented a new protocol that addresses all major requirements imposed by wireless ad-hoc sensor networks: energy-efficient connectionless communication combined with scalability, high mobility adaptability and speed. The protocol creates a virtual infrastructure to perform unicasting at the top level and support data aggregation. We studied its behavior by conducting extensive experiments and demonstrated that not only mobility can turn to be an advantage, but also increasing density can result a decrement of the energy spent without any additional cost.

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