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GEOMETRIC BROADCAST PROTOCOL FOR HETEROGENEOUS SENSOR NETWORKS

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We present Geometric Broadcast for Heterogeneous Sensor Networks (GBS), a novel broadcasting protocol for heterogeneous wireless sensor and actor networks. While broadcasting is a very energy expensive protocol, it is also widely used as a building block for a variety of other network layer protocols. Therefore, reducing the energy consumption by optimizing broadcasting is a major improvement in heterogenous sensor networking. GBS is a distributed algorithm where nodes make local decisions on whether to transmit based on a geometric approach. GBS does not need any neighborhood information and imposes very low communication overhead. GBS is scalable to the change in network size, node type, node density and topology. Furthermore it accommodates seamlessly such network changes, including the presence of actors in heterogeneous sensor networks. Indeed, GBS takes advantage of actor nodes, and uses their resources when possible, thus reducing the energy consumption by sensor nodes. Through simulation evaluations, we show that GBS is very scalable and its performance is improved by the presence of actors. At the best of our knowledge, GBS is the first broadcast protocol designed specifically for heterogeneous sensor and actor networks.

Keywords: Geometric Algorithm, Broadcast; Heterogeneous Wireless Sensor Networks.

1. Introduction

Heterogenous Wireless Sensor and Actor Networks (WSAN), supported by recent technological advances in low power wireless communications along with silicon integration of various functionalities such as sensing, communications, intelligence and actuations are emerging as a critically important disruptive computer class based on a new platform, networking structure and interface that enable novel, low cost, high volume applications [2,1,14,20] such as nuclear, biological and chemical attack detection and protection, home automation, battlefield surveillance and environmental monitoring [2,7,35].

Sensor nodes in general are extremely small, low-cost and low energy that possess sensing, signal processing and wireless communication capabilities. Sensors usually gather information about the physical world. Actor nodes are capable of making decisions and then performing appropriate actions. An example of actor nodes are robots able to sense, communicate and perform actions. Actor nodes in general are equipped with larger energy sources than sensors. Heterogeneous ad-hoc wireless networks of large numbers of such inexpensive but less reliable and accurate sensors combined with few actors can be used in a wide variety of commercial and military applications such as target tracking, security, environmental monitoring and system control.

In wireless sensor networks it is critically important to save energy. Battery power is typically a scarce and expensive resource in wireless devices. Current research on routing in wireless sensor networks mostly focused on protocols that are energy aware to maximize the lifetime of the network, that are scalable able to accommodate a large number of sensor nodes, and that are tolerant to sensor damage and battery exhaustion [4,6,22,38,39,42]. We have recently proposed an integrated power management and routing routing protocol [27] that enables tradeoffs between energy consumption and latency.

Since such energy considerations have dominated most of the research in sensor networks, the concept of delay was not a primary concern in most of the published work on sensor networks. However, in WSANs there may be a need to rapidly respond to sensor input, depending on the application. Moreover, so as to provide the right actions, sensor data must still be valid at the time of acting. Therefore, the issue of real-time communication is very important in WSANs since actions are performed on the environment after the sensing occurs [1,43].

The design of a good communication protocol for heterogeneous WSANs should be optimized for both energy consumption and delay. Communication protocols should take advantage of actor nodes, and use their resources when possible. Another important attribute is the scalability to change in network size, node type, node density and topology. Some nodes may die over time; some new nodes may join later; some nodes may move to different locations. A good communication protocol should seamlessly accommodate such network changes.

Network broadcasting is the process in which one node sends a packet to all other nodes in the network. Many applications as well as various unicast routing protocols use broadcasting or a derivation of it. Applications of broadcasting include location discovery, route establishment and querying. Broadcasting can also be used to discover multiple paths between a given pair of nodes. Many routing protocols propose the use of localized flooding for route maintenance.

Once the approximate location of a node is known, flooding restricted to an area limited around that location can be used to discover the exact location. In most of the cases the broadcast functionality is done using flooding, in which each node will be required to rebroadcast the packet whenever it receives the packet for the first time. Flooding generates many redundant transmissions, which may cause a more serious *broadcast storm problem* [25]. Consequently, flooding is very costly in energy and bandwidth.

Recently, a number of research groups have proposed more efficient broadcasting techniques. Centralized broadcasting schemes are presented in [3,15,16]. Algorithms in [24,31,33] utilize neighborhood information to reduce redundant messages in a Mobile Ad Hoc Network. Schemes in [19,36,21] deal with disseminating data in sensor networks. SPIN [19] and Directed Diffusion [21] protocols use application-specific data-naming and routing to reduce redundant transmissions. In [36] are presented protocols that achieve non-uniform information dissemination through which nodes are updated with varied accuracy or precision of information depending upon their requirements. However, the aim of broadcasting is application independent. Moreover, the data dissemination protocols are equivalent to flooding in the absence of information about which sensors are interested in the data. In this paper, we propose a broadcast protocol that meets the requirements of heterogeneous Wireless Sensor and Actor Networks.

In [13] we have introduced Broadcast Protocol Sensor (BPS) networks, explicitly designed for wireless sensor networks. While reducing energy consumption was the primary goal in our design, our protocol achieves good scalability and low latency. To achieve the primary goal of energy efficiency, we reduce the number of retransmissions by using a geometric approach. We assume that each node knows its location, also a requirement for various other routing protocols, sensing, target tracking and other applications. Various techniques like GPS [12], Time Difference of Arrival [32], Angle of Arrival [26] and Received Signal Strength Indicator [5] have been proposed enabling a node to discern its relative location. Recently, a range-free cost-effective solution[18] has been proposed for the same problem.

GBS presented here is an extension of our previous work [13]. GBS seamlessly handles the presence of actors by using their resources at the advantage of other nodes with less energy. The final result of GBS is a decrease in retransmitted packets, which leads to less energy consumption by sensors and faster transmission coverage of a given area. At the best of our knowledge, GBS is the first broadcast protocol designed specifically for heterogeneous sensor and actor networks.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 presents a summary of our BPS protocol. Section 4 presents Geometric Broadcast for Heterogeneous Sensor Networks. Section 5 describes our simulation model and discusses the simulation results. Section 6 concludes the paper.

2. Related work

Network-wide broadcasting is an essential feature for wireless networks. The simplest method for broadcast service is flooding. Its advantages are its simplicity and reachability. However, flooding generates abundant retransmissions for a single broadcast, resulting in battery power and bandwidth waste. Also, the re-transmissions of close nodes are likely to happen at the same time. As a result, flooding quickly leads to message collisions and channel contention. This is known as the broadcast storm problem [25].

The broadcast problem has been studied extensively for multihop networks. Optimal solutions to compute Minimum Connected Domination Set (MCDS) [16] were obtained for the case of each node knowing the topology of the entire network (centralized broadcast).

The broadcast protocol introduced in [3] completes the broadcast of a message in $O(D \times \log^2 n)$ steps, where 'D' is the diameter of the network and 'n' is the number of nodes in the network. From the result proved in [15], this protocol is optimal for networks with constant diameter.

For networks with a larger diameter, a protocol by Gaber et al. [16] completes the broadcast within $O(D + \log^5 n)$ time slots, and it is optimal for networks with diameter $D \in \Omega(\log^5 n)$.

The solutions presented in [3,15,16] are deterministic and guarantee a bounded delay in message delivery, but the requirement of each node knowing the entire network topology is a strong condition, impractical to maintain in wireless networks. Several broadcast protocols that do not require the knowledge of the entire network topology have been proposed. In a counter-based scheme [25], a node does not retransmit if it overhears the same message from its neighbors for more than a prefixed number of times. In a distance-based scheme [25], a node discards its retransmission if it overhears a neighbor within a distance threshold re-transmitting the same message.

Source Based Algorithm [28], Dominant Pruning [24], Multipoint Relaying [31], Ad Hoc Broadcast Protocol [29], Lightweight and Efficient Network-Wide Broadcast Protocol [33] utilize two-hop neighbor knowledge to reduce number of transmissions. But in large scale sensor networks, especially with high densities, the two-hop neighbor knowledge might impose very high memory overhead. A good classification and comparison of most of the proposed protocols is presented in [37].

It is also concluded that Scalable Broadcast algorithm (SBA) [28] and Ad Hoc Broadcast Protocol (AHBP) [29] perform very well as the number of nodes in the network increases. Both of these techniques are based on two-hop neighbor knowledge.

The Scalable Broadcast Algorithm [28] requires that all nodes have knowledge of their neighbors within a two-hop radius. This neighbor knowledge coupled with the identity of the node from which a packet is received allows a receiving node to determine if it would reach additional nodes by re-broadcasting. Two-hop neighbor knowledge is achievable via periodic hello messages, where each hello messages contains the node's identifier and the list of known neighbors. After a node receives hello messages from all its neighbors, it has two-hop topology information centered at itself.

AHBP [29] also requires that all nodes have knowledge of their neighbors within a two-hop radius. In AHBP, only nodes that are designated as a Broadcast Relay Gateway (BRG) within a broadcast packet header are allowed to rebroadcast the packet. BRGs are proactively chosen from each upstream sender, which is a BRG itself. A BRG selects sets of one-hop neighbors that most efficiently reach all the nodes within the two-hop neighborhood as subsequent BRGs. In[34] there are presented three location-aided broadcast protocols to improve communication overhead and shortcomings of various protocols are also summarized.

In self pruning methods [28,41,40], each node makes its local decision on forwarding status: forwarding or non-forwarding. Dai and Wu [9] compare the performance of various broadcast protocols for ad hoc networks based on self-pruning. Through rigorous simulations, they show that self-pruning helps in achieving high reliability and delivery ratio at the same time keeping the number of retransmissions low. For sensor networks, that are inherently very memory and energy constrained and because of high deployment densities, protocols based on self-pruning might not be appropriate. Self-pruning requires knowledge of at least two-hop neighbors. Sensors being very memory constrained, storing two-hop neighbor information might be prohibitive. Sensor nodes are highly energy constrained. Self-pruning needs periodic hello messages to keep up-to-date neighbor information that might again lead to significant energy consumption.

The drawback of the above Neighbor Knowledge methods is the need to store two-hop neighborhood information at each node. In large scale sensor networks, especially with high densities, this might impose very high memory overhead. For instance, at a modest density of 20 nodes per $R \times R$ region (R being transmission range), on average a node has over 250 two-hop neighbors and even if 10 bytes of data corresponding to each neighbor is stored, the total data is over 2.5KB. This is over 60% of free memory left in a sensor node [30]. Furthermore, keeping the neighbor information current involves additional communication overhead.

In Gossip-based routing [17], a node probabilistically (with a probability typically around 0.65) forwards a packet so as to control the spreading of the packet through the network. Though this simple mechanism reduces the number of redundant transmissions, there is still large room for improvement.

Several data dissemination protocols [19,36,21] have been proposed for sensor networks to disseminate data to interested sensors rather than to all sensors. A broadcast protocol is presented in [11] for regular grid-like sensor networks.

In this paper we propose a new protocol, which needs minimal neighborhood information; neither the neighboring node addresses nor their locations are needed. This eliminates the need for hello messages and related storage and communication overhead. Another property of GBS, as illustrated through simulations is that the number of retransmitting nodes gradually decreases as the number of nodes in the network increases.

3. Broadcast Protocol for Sensor Networks (BPS)

In this Section we give a short presentation of BPS [13]. BPS was designed as a modification to *The Covering Problem* that can be stated as follows: "What is the minimum number of circles required to completely cover a given two-dimensional space." Kershner [23] showed that no arrangement of circles could cover the plane more efficiently than the hexagonal lattice arrangement. Initially, the whole space is covered with regular hexagons, each side having a length of R, and then circles are drawn to circumscribe them.

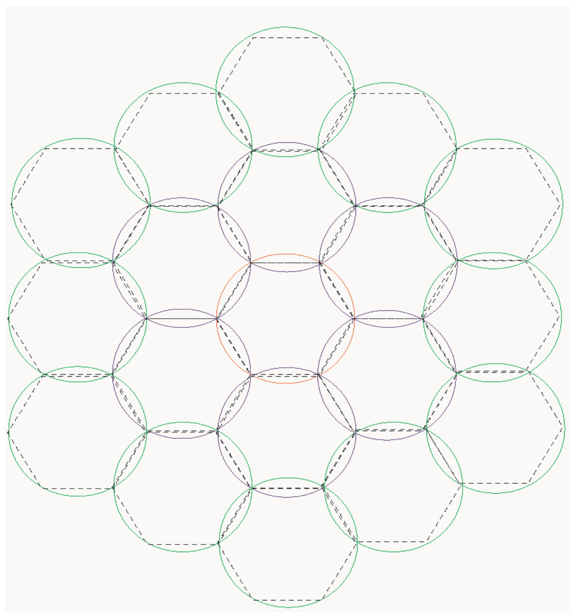

Fig. 1. Covering a plane with circles in an efficient way

A modified version of the Covering Problem can be stated as follows: "What is the minimum number of circles of Radius R required to entirely cover a two-dimensional space with the condition that the center of each circle lies on the circumference of at least one other circle."

If the range of a node is considered to be R, then the rationale behind the condition that the center of a circle should lie on the center of another circle is that a node has to receive a message for it to retransmit the message. A possible solution for the Modified-Covering Problem is shown in Fig. 2. As done for the covering problem, initially the whole region is covered with regular hexagons whose each side is R. Then, with each of the vertices as a center, circles of radius R are drawn.

The following properties of the vertices in Fig. 2 should be noted:

- *Property-1*: Each vertex v is joined to three other vertices.
- *Property-2*: The lines joining these three vertices to vertex v make an angle

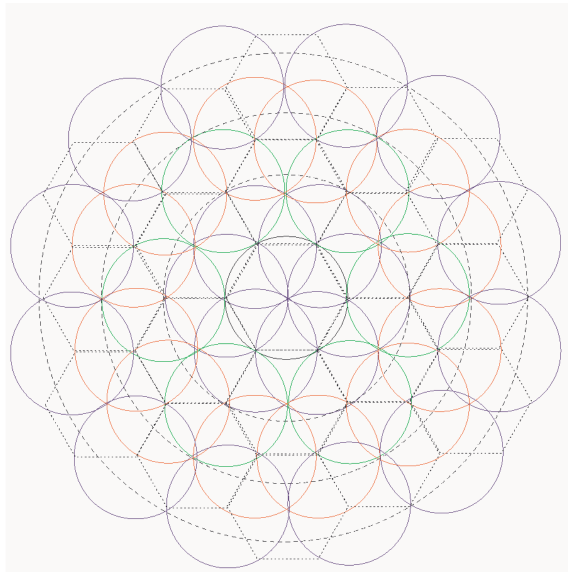

Fig. 2. Our Solution for the Modified-Covering Problem

of 120° (2 /3 radians) with each other.

- *Property-3*: Each vertex is at a distance of R from each of its neighboring vertices.

Thus, given a vertex v and one of its neighboring vertices, it is very easy to determine the other two neighboring vertices of vertex v, using the above properties. The approach followed here to solve the Modified-Covering problem is for an ideal case scenario. We use the same approach to achieve broadcasting in a more general case, where there need not be any node at the optimal locations. In this case Fig. 2 can be distorted considerably. Even when the distortion is very large, the number of transmissions required to cover the whole region remains very low [13].

In [13] we have shown through simulations that our BPS protocol outperforms other broadcasting protocols.

4. Geometric Broadcast for Heterogeneous Sensor Networks (GBS)

In this section, we present the Geometric Broadcast for Sensor and Actor Networks (GBS). We make use of the fact that actor nodes are more powerful and have a larger energy/transmission radius than sensor nodes. Thus, an actor node can cover much more area than a normal sensor node and, hence we would like the actor nodes to transmit before the sensors do.

We assume that each sensor node knows the location of its nearest actor node and the number of its actor neighbors. We also assume that each actor node knows the locations of other actor nodes. Let S be the Source node that generates the broadcast message. S sends the broadcast message first to one of the actor nodes, which in turn sends it to other actor nodes (if present). The actor nodes then broadcast the message to all of their neighbors, resulting in coverage of a large portion of the network. Then, only few other sensors (that are selected based on some criteria described later in this section) transmit to cover the remaining region.

Algorithm

Let R be the transmission range of a sensor and $R_a = k \times R$ be the transmission range of an actor node. The protocol execution at the actor nodes is different from that at sensor nodes. The header of a broadcast message is formatted to contain $3 \times k$ locations if transmitted by an actor or two locations L_1 and L_2 if transmitted by a sensor.

4.1. *Actor Node Algorithm*

The protocol executed at the actors is described below:

(1) The source node that generates the broadcast message sends the packet to its nearest actor, which in turn forwards it to other actor nodes (if present) in the network.
(2) Each actor calculates $3 \times k$ strategic locations as follows:
    - The actor selects some point P randomly on its circumference.
    - The remaining $3 \times k - 1$ points are the points on the circumference such that each is at a distance of $2R$ from other points.
(3) The actor broadcasts the packet with these $3 \times k$ points stored in the header of the packet.

4.2. *Sensor Node Algorithm*

The protocol execution at sensor nodes is as follows:

(1) A node M, upon receiving a broadcast packet, first determines if the packet can be discarded. A packet can be discarded under any of the following conditions:
    - If the node has transmitted the packet earlier.
    - If a node which is very close has already transmitted this packet, i.e., if $d_n < Th$.
    - if the node M is a neighbor of more than one actor node.
(2) If the packet is not discarded, M determines if it received the packet directly from an actor node.
    - If yes, M first finds the location L in the header of the message that it is closest to. It computes its distance l from L and then delays the packet rebroadcast by a delay d given by $d = \frac{l}{R}$.
    - Else, if M has not received the packet directly from the source S, but from some other node K, then it uses properties 1, 2 and 3, mentioned in Section 3, to find the nearest strategic location. The packet transmission is delayed by $d = \frac{l}{R}$.

(3) After the delay d, M again determines if it has received the same packet again and if the packet can be discarded (for the same reasons mentioned above). Thus, delaying enables a node to decide if it is the closest node to the strategic location. If the packet cannot be discarded, M updates L_1 to the location of the node from which it received the packet and L_2 to its location, sets d to zero and transmits.

A node M does not broadcast a message if it is neighbor to more than one actor. In such a scenario, M is in the overlapping region of the coverage regions of the actors and so is the case of most of neighbors of M. Thus, even if M retransmits the message, in most cases it would not reach any sensor that is not covered by the actors.

Fig. 3 shows the rationale behind the selection of $3 \times k$ locations when $R_a = 2 \times R$. The delay is used to make a node decide whether it is the closest node to the strategic location. Low delay values decrease the time needed to broadcast a message all over the network, while high delay values help reduce redundant transmissions in instances where two nodes are of about same distance from the strategic location. The delay function we used causes a packet to be delayed a maximum of 50 ms per retransmission, though typically this value lies around 10 ms. In dense networks, the delay values are much less than 10 ms.

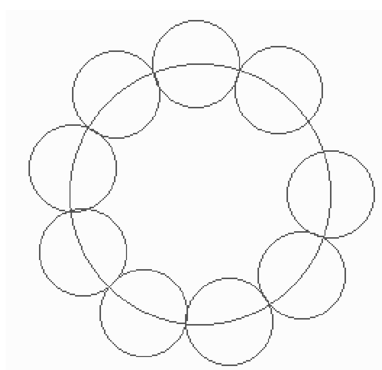

Fig. 3. Broadcasting from an Actor node

The computational complexity of GBS is negligible; when compared to flooding, the major additional computation is finding the node's distance to the nearest optimal point according to the modified covering problem, which can be easily computed using properties 1-3 mentioned in Section 3. The only insignificant bandwidth overhead is the addition of new header fields to carry location information of two nodes.

5. Performance Evaluation

We have developed a simulator using OMNET++, a discrete event simulation framework [10], to evaluate the performance of our protocol. In [13] we compared our BPS with blind flooding. We also compared BPS with Ad Hoc Broadcast Protocol (AHBP) [29] as AHBP is one of the protocols (SBA [28] is the other) that approximates MCDS closely [37]. A wireless network of different physical areas and different shapes with different numbers of nodes was simulated.

Here we compare the performance of BPS to the extended GBS protocol, in case of heterogeneous wireless networks that includes both sensor and actor nodes.

We consider two different network scenarios:

(1) Wireless Sensor Networks (WSNs) consisting of sensors with similar capabilities.
(2) Wireless Sensor and Actor Networks (WSANs) consisting of sensor and actor nodes.

The model parameters and limits on transmission bit rates and energy ratings are set according to Crossbow MICA2 sensor nodes [8]. Energy consumption in the model is based on the amount of the current draw that Crossbow MICA2 sensor node's radio transreceiver uses [8].

Fig. 4 shows the broadcast pattern for a network of $6R \times 6R$ with 1 actor whose radius is $2R$. There are 225 nodes and 2% nodes are uncovered with 36 transmissions.

Fig. 4 and Fig. 5 show the effect of distortion in the case of random distributed nodes.

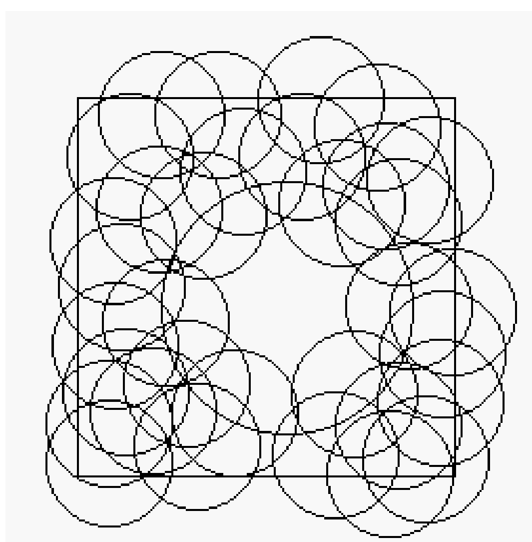

Fig. 4. Broadcast in a WSAN: 1 actor and 225 sensors

In Fig. 5 is shown for a network of $10R \times 10R$ with two actor whose radius is

$3R$. There are 625 nodes and 3.8% nodes are uncovered with 64 transmissions.

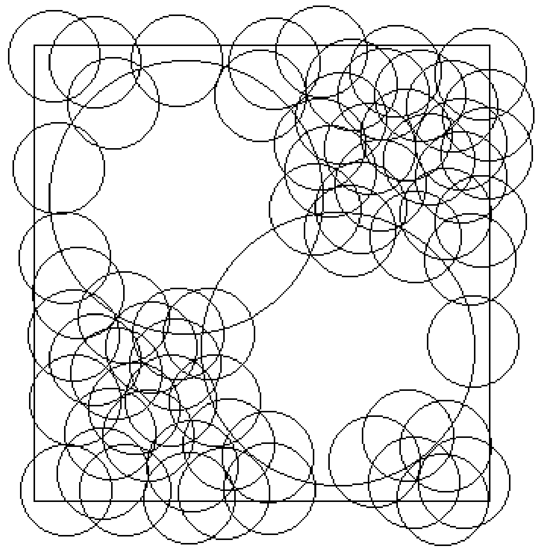

Fig. 5. Broadcast in a WSAN with a configuration of two actors and 525 sensors.

In our setup, 40 nodes were made to generate traffic to random destinations at different rates varying from 1packet/sec up to 16 packets/sec. Each data packet had a size of 64 bytes including a header of 12 bytes of header information and hence length beacon and other control packets are assumed to be 12 bytes. Nodes were randomly deployed with uniform distribution with various densities. The energy consumption for switching the radio from idle to sleep modes and vice versa is assumed to be negligible and hence not considered. The location is assumed to be available via GPS or other localization means and thus is not simulated.

Fig. 6, 7 and 8 present the performance of GBS in a sensor network for different network size, density and configuration. As expected, GBS is very scalable, the number of transmissions is reduced when the density increases. This is due to the geometric approach used in GBS. We have compared network configurations with and without actors. As shown in the results of Fig. 6, 7 and 7, GBS takes advantage of the presence of Actors to reduce the number of retransmissions, therefore lowering the energy consumption and increasing the speed to cover the whole area.

6. Conclusion

We presented Geometric Broadcast for Wireless Sensor and Actor Networks (GBS), a novel protocol for use in heterogeneous Wireless Sensor and Actor Networks.

GBS is a distributed algorithm where nodes make local decisions on whether to transmit based on a geometric approach. GBS does not need any neighborhood

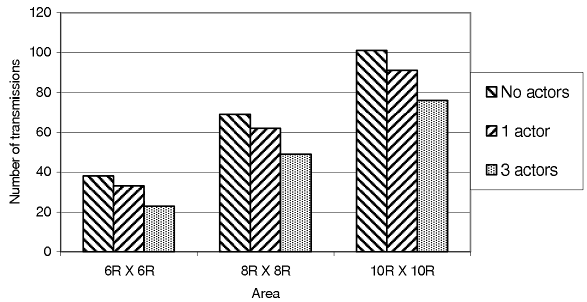

Fig. 6. Performance of GBS in different networks. Density = 16. Radius of actor node is three times that of sensors.

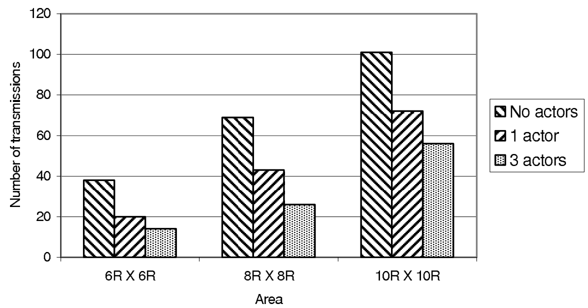

Fig. 7. Performance of GBS in different networks. Density = 10. Radius of actor node is three times that of sensors.

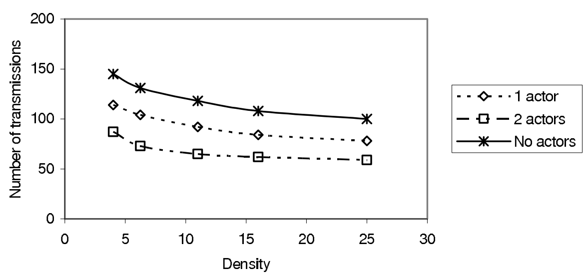

Fig. 8. Performance of GBS with respect to density. Network area = 10R X 10R. Radius of actor node is three times that of sensors.

information and imposes very low communication overhead.

GBS is scalable to the change in network size, node type, node density and topology. GBS seamlessly accommodates such network changes, including the presence of actors in heterogeneous sensor networks.

Indeed, GBS takes advantage of actor nodes, and uses their resources when possible, thus reducing the energy consumption by sensor nodes. Through simulation evaluations, we showed that GBS is very scalable and its performance improves by the presence of actors.

Acknowledgments

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