Network Coverage Sensitive Pseudo Geometric Broadcast Protocols in Wireless Sensor Networks

Chunchao Liang†, Sunho Lim†, Manki Min§, and Wei Wang‡

***Abstract*—Due to the deployment limitations of global positioning system (GPS), a pseudo geometric broadcast approach is investigated in resource constrained wireless sensor networks (WSNs). Without relying on the GPS support, a set of nodes closely located in a strategic position is judiciously searched and identified as a forwarding node. In this paper, we first propose both enhanced ad hoc broadcast protocol (AHBP) with target forwarding nodes (EBP($|N_f|$)) and node distribution sensitive broadcast (NDS) to maximize the network coverage while minimizing the number of broadcasts. Second, we revisit prior AHBP and approximating neighbor nodes based broadcast protocol (Approx) for investigation in terms of network coverage. For performance comparison study, we modify the AHBP and broadcast protocol for sensor networks (BPS), denoted as BPS*. We conduct extensive simulation experiments using OMNeT++ and analyze the performance of protocols. Extensive simulation results indicate that the proposed EBP($|N_f|$) and NDS protocols achieve competitive performance and can be a viable approach in WSNs.**

***Index Terms*—Performance analysis, pseudo geometric broadcast, wireless sensor networks.**

I. Introduction

A set of nodes located in a strategic position is selected as a forwarding node to maximize the network coverage, while minimizing the number of rebroadcasts in geometric broadcast protocols. Each node is often equipped with an on-board global positioning system (GPS) and selects the best forwarding nodes based on its adjacent nodes' location. Although GPSes have been deployed in diverse networking areas and are increasingly popular, positioning inaccuracy, non-negligible deployment cost and energy consumption, and intermittent availability of GPS signals in indoors often limit their deployment in resource-constrained multi-hop wireless networks. For example, a NAVSTAR GPS has about 50 to 100 (m) error bounds [1], which can negatively affect the communication performance. More importantly, a blind broadcast is inefficient in terms of the network coverage and even harmful because it can cause redundant retransmissions and packet contentions and collisions.

In this paper, we propose network coverage sensitive broadcast protocols that can maximize the network area covered in resource-constrained wireless sensor networks (WSNs). Without relying on the GPS support, a *pseudo* geometric broadcast approach is deployed and embedded into the proposed broadcast protocols, where a set of nodes closely located in a strategic position is judiciously searched. The performance of proposed broadcast protocols is evaluated and compared with three other competitive broadcast protocols. Our contributions are summarized in two-fold:

- We first propose two pseudo geometric broadcast protocols: enhanced ad hoc broadcast protocol (AHBP) with target forwarding nodes (EBP($|N_f|$)) and node distribution sensitive broadcast (NDS). A set of nodes is selected as a forwarding node based on the number of two-hop neighbor nodes covered in the network. Here, $|N_f|$ is the number of forwarding nodes.
- Second, we revisit prior AHBP and approximating neighbor nodes based broadcast protocol (Approx) for investigation in terms of network coverage. For performance comparison study, we modify prior AHBP [2] to work in WSNs. A variation of the GPS supported broadcast protocol for sensor networks (BPS) [3], denoted as BPS*, is also modified by adding a sender-initiated broadcast approach.

We conduct extensive simulation experiments and multi-dimensional analyses using OMNeT++ [4]. We evaluate the aforementioned broadcast protocols in terms of packet delivery ratio, number of broadcasts, and propagation delay by changing the node density and network size. Simulation results indicate that the proposed EBP($|N_f|$) and NDS protocols show competitive performance and can be viable approaches in resource-constrained WSNs.

The rest of paper is organized as follows. The prior work is reviewed in Section II. We revisit two pseudo geometric broadcast protocols for investigation and present two new approaches in Section III. Section IV is devoted for performance evaluation and analysis. Finally, we conclude the paper with future research direction in Section V.

II. Related Work

Gossiping and its variations [5] extended from a conventional flooding are to minimize the impact of the broadcast storm problem [6] in multi-hop wireless networks. Each node decides whether to forward a packet with a retransmission probability p, which can be updated under the consideration of dissemination coverage, latency, and communication overhead. In [7], each node adaptively adjusts its forwarding probability based on the Weibull model. Pseudo broadcast protocols with a sender-initiated approach [2], [8] have been proposed, in which a sender selects a set of forwarding nodes located

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in strategic positions. In [2], an ad hoc broadcast protocol (AHBP) maintains two-hop neighbor nodes by periodically exchanging a one-hop *Hello* message. A sender node keeps searching the forwarding nodes until all two-hop neighbor nodes are covered. In [8], a sender node also selects a set of strategically located forwarding nodes (i.e., closest to the border of communication range) to maximize the network coverage.

An ideal optimal flooding [9] is considered to find the minimum number of circles to cover the entire network area, in which the distance between two circles' center is less than or equal to R. The efficiency is defined as the ratio of the entire network to the total areas covered by all broadcast packets. As pointed out, the efficiency is 1 if every node receives a broadcast packet once but the efficiency of any flooding cannot exceed 0.6. Under the GPS support, however, a virtual hexagon-based coverage approach and its variations [9], [3], [10] can significantly reduce the number of redundant rebroadcasts. Three or six forwarding nodes located in a strategic position are selected to minimize the overlapped network area covered. In a hexagon-flooding scheme [9], an initial packet sender first selects three one-hop neighbor nodes located at the vertices of hexagon as a forwarding node. Then each forwarding node selects another two forwarding nodes thereafter for rebroadcast. This scheme achieves 68% of the upper-bound efficiency of flooding.

In summary, since the support of GPS may not always be available in practice, an efficient GPS-free broadcast protocol is critical in resource-constrained WSNs. Unfortunately little effort has been devoted in exploring the performance comparison study in the realm of pseudo geometric broadcast protocols.

III. Network Coverage Sensitive Pseudo Geometric Broadcast Protocols

In this section, we first discuss an issue on the network coverage with preliminary results. Then we present the proposed pseudo geometric broadcast protocols along with two competitive broadcast protocols in WSNs. In this paper, we deploy a sender-initiated broadcast approach in pseudo geometric broadcast protocols, where a packet sender selects a set of forwarding nodes based on its local policy. Each node is aware of its one-hop neighbor nodes by exchanging a single hop *Hello* packet piggybacked with its *id*. Then each node can also be aware of its two-hop neighbor nodes by piggybacking its one-hop neighbor nodes' ids.

A. Network Coverage

Due to unreliable or lossy wireless link, frequent packet collisions, and lack of centralized coordination, broadcast packets are often prematurely terminated while they are propagated in multi-hop WSNs. In Fig. 1, we conduct an experiment with a simple broadcast approach. Each packet sender selects a single one-hop forwarding node in a 100×100 (m^2) rectangular network, where nodes (i.e., 300 to 2,000) are randomly distributed. A node closely adjacent to the largest number of its uncovered one-hop neighbor nodes, which are in fact two-hop neighbor nodes of the packet sender, is selected as a forwarding node to maximize the network area covered. The packet delivery ratio (PDR) is measured against the different number of deployed nodes in the network. The communication range of each node, R, is 10 (m). Although the number of deployed nodes increases, PDR does not increase much and is still quite low, less than 40%. Thus, it is essential to judiciously select multiple forwarding nodes to guarantee a certain level of network coverage without causing the premature termination of broadcast packets.

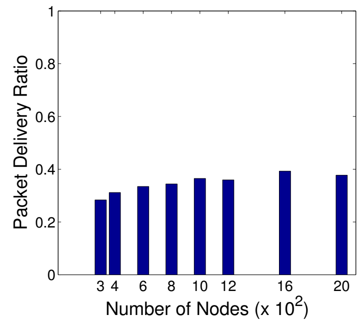


Fig. 1. A set of packet delivery ratios against the different number of deployed nodes.

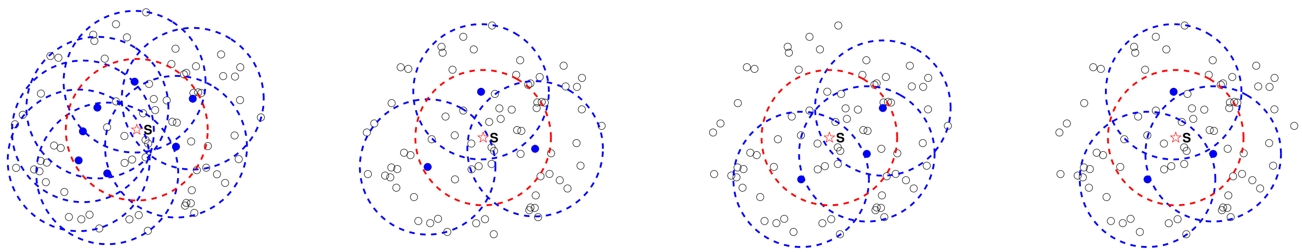
B. Revisiting Pseudo Geometric Broadcast Protocols

In this subsection, we analyze prior pseudo geometric broadcast protocols in terms of network coverage and compare their major broadcast operations.

1) Ad Hoc Broadcast Protocol (AHBP) [2]: As a connected dominating set (CDS) based approach, a sender repeatedly selects a forwarding node, called as a broadcast relay gateway (BRG), until entire two-hop neighbor nodes are covered. The sender first selects a one-hop neighbor node as a BRG (e.g., n_i) and constructs a local topology graph based on a two-hop neighbor table. The topology graph is reduced by removing the edges of adjacent nodes of n_i. The sender repeatedly selects a BRG, constructs its topology graph, and removes the edges of its adjacent nodes until all two-hop neighbor nodes are covered by at least one BRG. If a two-hop neighbor node of n_s is only adjacent to a one-hop neighbor of n_i, then n_i becomes a BRG. Major operations of the AHBP are summarized in Fig. 3.

In Subfig. 2(a), seven nodes are selected as a forwarding node but they are not always located at the boundary of the sender's communication range. The sender greedily selects a number of forwarding nodes not to miss any disconnected two-hop neighbor node. Thus, the AHBP shows more overlapped broadcast areas compared to other protocols.

2) Approximating Neighbor Nodes based Broadcast Protocol (Approx) [8]: A sender selects a set of forwarding nodes near the boundary of its communication range to maximize the network area covered. A virtual hexagon-based coverage is considered to minimize overlapped broadcast areas. A rationale behind this protocol is that each node shares the same or similar number of neighbor nodes in a dense WSN. A two-step approach is deployed to identify a set of forwarding nodes.



(a) AHBP (b) Approx (c) EBP(3) (d) NDS

Fig. 2. A different set of forwarding nodes is selected based on the protocols. Here, both source (i.e., n_s) and forwarding nodes are marked by a star and shaded circles, respectively. The communication range is represented by a dashed line.

Notations:

- n_s: A sender node holding a packet to broadcast.
- $n^*_{s,i}$: A one-hop neighbor node, n_i, of n_s.
- $\{n^*_s\}$: A set of one-hop neighbor nodes of n_s.
- $n^+_{s,i,j}$: A two-hop neighbor node, n_j, of n_s via $n^*_{s,i}$.
- $\{n^+_{s,i}\}$: A set of two-hop neighbor nodes of n_s via $n^*_{s,i}$.
- $\{n^+_s\}$, $|\{n^+_s\}|$: A set of two-hop neighbor nodes of n_s,

where $\{n^+_s\}$ = $\sum^i\{n^+_{s,i}\}$, and its cardinality.

- $\{F_s\}$: A set of forwarding nodes of n_s.

$\{F_s\}$ = $\emptyset$;
for $\forall\ n^*_{s,i} \in \{n^*_s\}$ **do**
  for $\forall\ n^+_{s,i,j} \in \{n^+_{s,i}\}$ **do**
    if $n^+_{s,i,j} \notin \{n^+_{s,k}\}$, where $i \neq k$
      $\{F_s\}$ = $\{F_s\} \cup n^*_{s,i}$;
      Delete $\{n^+_{s,i}\}$ from $\{n^+_s\}$;
while $\{n^+_s\} \neq \emptyset$ **do**
  Find $n^*_{s,i}$ with the largest $|\{n^+_{s,i}\}|$;
  $\{F_s\}$ = $\{F_s\} \cup n^*_{s \cdot i}$;
  Delete $\{n^+_{s,i}\}$ from $\{n^+_s\}$;

Fig. 3. The pseudo code of the AHBP.

First, a sender (n_s) searches the nodes near its communication range by counting its one-hop neighbor nodes ($n^*_{s,i}$), $|G_s|$, and the number of one-hop neighbor nodes' neighbor nodes, $|G_i \cap G_s|$. Then the sender checks if $n^*_{s,i}$ satisfies $\frac{|G_i \cap G_s|}{|G_s|}$ $\approx$ 39.1% or 39.1% + ϵ. If both sender and its one-hop neighbor nodes share their communication range about 39.1%, each node is then most likely located at the border of the other node's communication range. Second, the sender further searches a pair of nodes located at $\sqrt{3}R$ among the nodes that satisfy the previous step, where R is the communication range of each node. The sender counts the number of n^*_i's and n^*_j's common one-hop neighbor nodes, $|G_i \cap G_j|$. Then the sender checks if n^*_i and n^*_j satisfy $\frac{|G_i \cap G_j|}{|G_s|}$ $\approx$ 5.8% or 5.8% + δ, and selects best three forwarding nodes that satisfy the previous two steps. If two nodes share their communication range about 5.8%, they are most likely located at $\sqrt{3}R$ apart each other.

Note that in case of a sparse or non-uniform network, the sender may not find enough number of nodes that satisfy the previous two steps. Especially, the assumption of uniform communication range may not always be applicable in WSNs. For example, each node may have variable communication ranges in an energy harvesting WSNs [11]. In light of these, the Approx provides a flexibly way to search additional number of forwarding nodes by increasing the ϵ or δ. Here, ϵ and δ are system parameters and provide a margin to the sender for flexibly selecting the forwarding nodes [8]. Major operations of the Approx are summarized in Fig. 4. Here, the Approx selects the best three forwarding nodes in $\{F_s\}$.

Notations:

- n_s, $n^*_{s,i}$, $\{n^*_s\}$, $\{F_s\}$, ϵ, δ: Defined before.
- n^*_i: One-hop neighbor nodes of n_i.
- $|n^*_s|$: A number of one-hop neighbor nodes of n_s.
- $\{B_s\}$: A set of one-hop neighbor nodes closely located to the boundary of communication range of n_s.

$\{B_s\}$, $\{F_s\}$ = $\emptyset$;
for $\forall\ n_i \in \{n^*_s\}$ **do**
  if $|\{n^*_i\} \cap \{n^*_s\}| \leq |n^*_s| \times$ 39.1% + ϵ
    $\{B_s\}$ = $\{B_s\} \cup n^*_{s,i}$;
for $\forall\ n_i, n_j, n_k \in \{B_s\}$, where $i \neq j$, $k \neq j$, $k \neq i$ **do**
  if ($|\{n^*_i\} \cap \{n^*_j\}| \leq |n^*_s| \times$ 5.8% + δ) $\wedge$ ($|\{n^*_i\} \cap \{n^*_k\}| \leq |n^*_s| \times$ 5.8% + δ) $\wedge$ ($|\{n^*_j\} \cap \{n^*_k\}| \leq |n^*_s| \times$ 5.8% + δ)
    $\{F_s\}$ = $\{n_i, n_j, n_k\}$;

Fig. 4. The pseudo code of the Approx.

In Subfig. 2(b), three nodes are selected as a forwarding node. They are near the boundary of the sender's communication range and approximately $\sqrt{3}R$ apart each other. There are two nodes located closer to the boundary of communication range than that of the selected forwarding nodes. However, they are not selected as a forwarding node because they are closely located each other, and thus the condition of the second step is not satisfied.

C. Proposed Pseudo Geometric Broadcast Protocols

In this subsection, we propose two network coverage sensitive pseudo geometric broadcast protocols and present their major broadcast operations.

1) Enhanced AHBP with Target Forwarding Nodes (EBP($|N_f|$)): Since a sender aggressively selects multiple forwarding nodes in the AHBP, the broadcast area of a forwarding node can be overlapped with others' significantly. Thus, the neighbor nodes of the forwarding node may receive the same broadcast packet multiple times. In this paper, we propose an enhanced AHBP with target forwarding nodes, called EBP($|N_f|$), to reduce the overlapped broadcast areas. Here, $|N_f|$ is a number of forwarding nodes. Rather than blindly selecting a forwarding node and building its local topology graph, a sender selects a one-hop neighbor node as a forwarding node that can cover the maximum number of two-hop neighbor nodes based on a two-hop neighbor table. The sender considers only uncovered two-hop neighbor nodes to select additional forwarding node. The sender continues selecting a forwarding node one by one until all two-hop neighbor nodes are covered or $|N_f|$ forwarding nodes are chosen. Major operations of the EBP($|N_f|$) are summarized in Fig. 5.

Notations:

• $n^*_{s,i}$, $\{n^+_{s,i}\}$, $|\{n^+_{s,i}\}|$, $\{n^+_s\}$, $\{n^+_{s,i,j}\}$, $\{F_s\}$, $|N_f|$: Defined before.

$\{F_s\}$ = $\emptyset$;
while $|N_f| > 0$ **do**
Find $n^*_{s,i}$ with the largest $|\{n^+_{s,i}\}|$;
$\{F_s\}$ = $\{F_s\} \cup n^*_{s,i}$;
Delete $\forall$ $\{n^+_{s,i,j}\}$ from $\{n^+_s\}$;
$|N_f|$ = $|N_f|$ - 1;

Fig. 5. The pseudo code of the EBP($|N_f|$).

In Subfig. 2(c), the EBP(3) selects three forwarding nodes and results in 12 uncovered two-hop neighbor nodes. The number of forwarding nodes is significantly reduced compared to the AHBP. Unlike the Approx, however, the locations among forwarding nodes are not well-balanced. For example, the area of network coverage can be distorted and this distorted effect may also propagate.

2) Node Distribution Sensitive Broadcast (NDS): In the Approx, a sender approximates the location of one-hop neighbor nodes and selects a set of forwarding nodes near a strategic position, i.e., the boundary of communication range of a sender. An optimized broadcast protocol for sensor networks (BPS) [3] also selects a set of forwarding nodes near a strategic position. In the BPS, unlike aforementioned pseudo geometric broadcast protocols, each node is equipped with a GPS and utilizes the location information of its neighbor nodes. When a node receives a broadcast packet, it discards the packet if it has been transmitted from a closely located neighbor node, i.e., less than a threshold value ($0.4R$). If not, the node selects a forwarding node that is the nearest to the strategic location, i.e., hexagon's vertex. Then the node executes a backoff procedure before transmission, in which the backoff period is proportional to the distance to the corresponding strategic location. The drawback is that positional inaccuracy of GPS can significantly affect the communication performance.

Both Approx and BPS are designed to minimize the number of broadcasts by maximizing the distance between the sender and forwarder nodes for each broadcast. However, the distribution of nodes to be covered is not fully considered in selecting a set of forwarding nodes. In this paper, we also propose a node distribution sensitive broadcast (NDS) to maximize the network coverage. A sender repeatedly searches one-hop neighbor nodes and counts the number of two-hop neighbor nodes that each neighbor node can cover. Three one-hop neighbor nodes that cover the maximum number of two-hop neighbor nodes are selected as the forwarding nodes. Major operations of the NDS are summarized in Fig. 6. Here, the NDS selects the best three forwarding nodes in $\{F_s\}$.

Notations:

• n_s, $\{n^*_s\}$, $\{n^+_i\}$, $\{F_s\}$: Defined before.

• $\{F^+_s\}$, $|\{F^+_s\}|$: A set of two-hop neighbor nodes of n_s via $\{F_s\}$, and its cardinality.

$\{F_s\}$ = $\emptyset$;
for $\forall$ n_i, n_j, $n_k \in \{n^*_s\}$, where $i \neq j$, $k \neq j$, $k \neq i$ **do**
if $|\{n^+_{s,i}\} \cup \{n^+_{s,j}\} \cup \{n^+_{s,k}\}| > |\{F^+_s\}|$
$\{F_s\}$ = $\{n_i, n_j, n_k\}$;

Fig. 6. The pseudo code of the NDS.

In Subfig. 2(d), although these three forwarding nodes are not near the boundary of communication range of the sender, the NDS covers equal or more number of nodes than that of the Approx.

IV. Performance Analysis

We conduct extensive simulation experiments using OMNeT++ [4] for performance evaluation study. A square network area is deployed with different node densities, where a number of statically located nodes are randomly distributed in the network. In this paper, we define a node density as the number of nodes deployed in a rectangular area, $R \times R$, where R is the communication range of each node, 10 (m). A single source node is located at the center of network and broadcasts a 2 Kbyte data packet [8]. The radio model is based on the CC2420 with a nominal data rate of 250 Kbps [12]. The radio propagation model is also based on the free-space model. The simulation results are the average of 100 simulation runs.

We compare the performance of pseudo geometric broadcast protocols: *AHBP*, *Approx*, *EBP($|N_f|$)*, and *NDS*. The AHBP is modified to work in WSNs. The proposed EBP($|N_f|$) is evaluated with three to six target forwarding nodes, EBP(3) to EBP(6). For performance comparison, we also modify the GPS supported BPS by adding a sender-initiated approach,

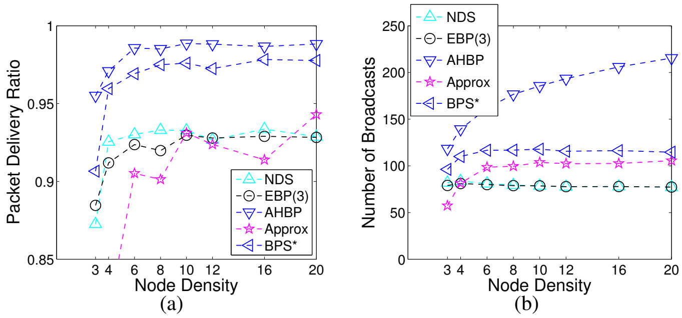


Fig. 7. Comparisons of packet delivery ratio and number of broadcasts.

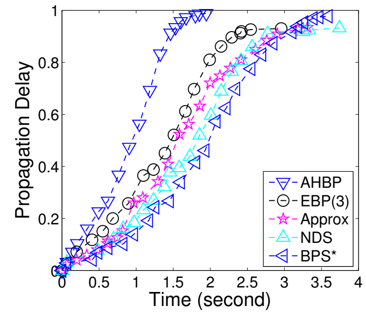


Fig. 8. Comparison of propagation delay.

denoted as *BPS**, where a sender selects a set of forwarding nodes located in a strategic position (i.e., hexagon vertex). Only designated forwarding nodes will rebroadcast a packet after a random backoff. We measure the performance in terms of packet delivery ratio (PDR), number of broadcasts, and propagation latency. Here, a 10R$\times$10R network size is used for entire experiments unless otherwise specified.

First, Fig. 7 shows the PDR and number of broadcasts against the node density. In Subfig. 7(a), all protocols achieve high PDR for entire node densities except the Approx. Since the Approx is designed primarily for a dense network, as pointed out in [8], it shows the lowest PDR in the lower node densities. This is because three well-balanced forwarding nodes are not selected. The AHBP shows the highest PDR because it aggressively selects a number of forwarding nodes to maximize the network coverage. Although a less number of forwarding nodes is selected, the BPS* still shows competitive performance with the AHBP because only strategically located nodes are selected as a forwarding node. The proposed EBP(3) and NDS show higher PDR than that of the Approx. As we can expect, the Approx shows the higher PDR in the largest node density.

In Subfig. 7(b), The AHBP shows the largest number of broadcasts as the node density increases. This is because more number of forwarding nodes is selected to cover more number of deployed nodes in the network. The BPS* and Approx show a scalable performance as the node density increases because the same number of forwarding nodes is selected regardless of the node density. The proposed EBP(3) and NDS show the lowest number of broadcasts because well-balanced forwarding nodes are selected to minimize the number of rebroadcasts.

Second, Fig.8 shows the packet propagation delay with 1,000 nodes deployed in the network. The AHBP shows the shortest delay because more number of forwarding nodes is selected for rebroadcasting than that of other protocols. The Approx, EBP(3), and NDS show competitive performance. Note that although these three protocols cannot achieve 100% PDR, they show shorter delay than that of the BPS*, in which strategically located forwarding nodes are selected based on the location information.

Third, we further compare the performance of the EBP($|N_f|$) and AHBP in Fig. 9. In Subfig. 9(a), the AHBP

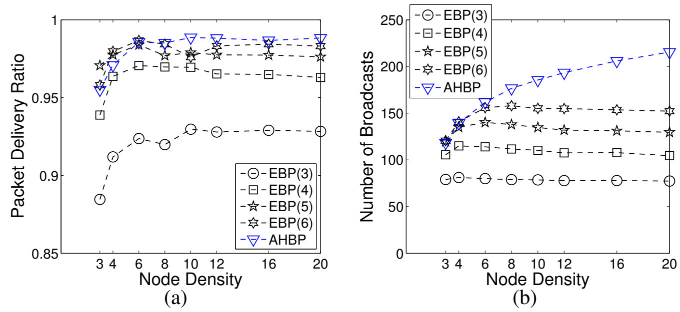


Fig. 9. Comparisons of packet delivery ratio and number of broadcasts in the EBP and AHBP.

shows the highest PDR but the EBP($|N_f|$) also shows competitive performance, i.e., more than 95%. As the $|N_f|$ increases, the PDR increases. The EBP(3) shows the lowest PDR (i.e., $>$ 90%). Since only a set of nodes that covers the largest number of two-hop neighbor nodes is selected as a forwarding node, the EBP($|N_f|$) can achieve as high PDR as the AHBP when $|N_f| \geq 4$. In Subfig. 9(b), the EBP($|N_f|$) shows a scalable performance as the node density increases. Since the AHBP aggressively selects a number of forwarding nodes for rebroadcasting, the number of broadcasts increases as the node density increases. The performance results indicate that the EBP($|N_f|$) can achieve competitive PDR and the lower number of broadcasts with the less number of forwarding nodes compared to the AHBP. Note that the EBP(4) can already achieve 96% PDR with the modest number of forwarding nodes.

Finally, we measure the PDR and number of broadcasts against four different network sizes (i.e., 4R$\times$4R, 7R$\times$7R, 15R$\times$15R, and 20R$\times$20R) in Figs. 10 and 11, respectively. In Fig. 10, the AHBP shows the highest PDR for entire node densities and network sizes. The BPS* also shows competitive performance with the AHBP. Under the small network sizes (i.e., 4R$\times$4R and 7R$\times$7R), the Approx, EBP(3), and NDS show low and fluctuated PDR because of the less number of deployed nodes in the networks. As the network size increases, however, these three protocols are close to 95% PDR. The Approx does not perform well with the low node density for entire network sizes.

In Fig. 11, the EBP(3) and NDS show the lowest number of broadcasts for entire node densities and network sizes.

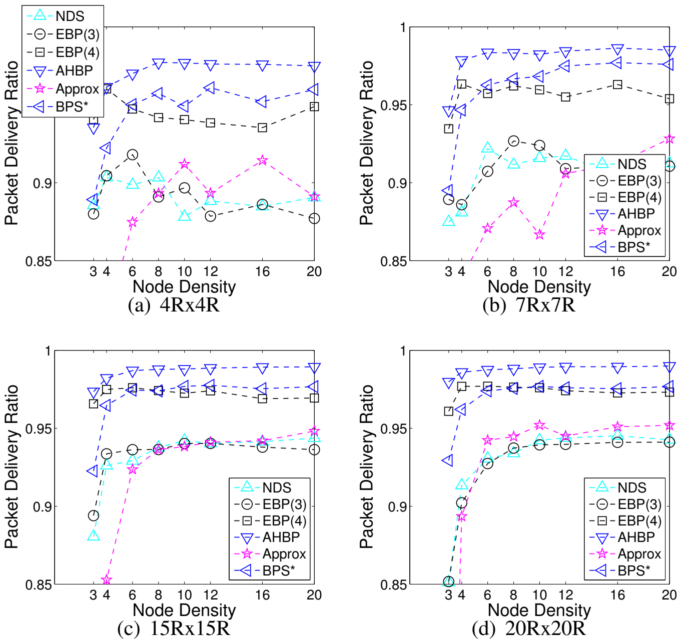


Fig. 10. Comparisons of packet delivery ratio against different network sizes.

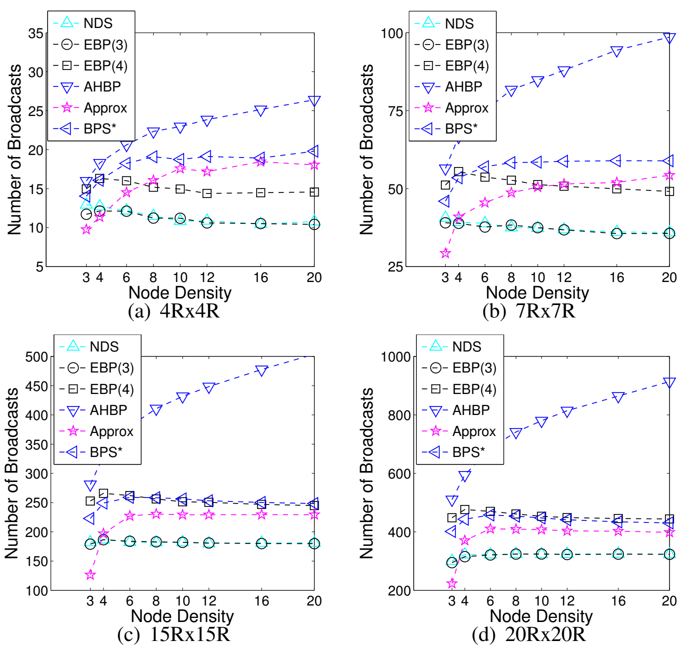


Fig. 11. Comparisons of number of broadcasts against different network sizes.

Since these protocols judiciously select a set of forwarding nodes that can cover the largest number of two-hop neighbor nodes, the number of broadcasts is minimized and shows a scalable performance. Other protocols also show a scalable performance except the AHBP. Note that the NDS shows a similar or slightly higher performance compared to the EBP(3). Although the NDS repeatedly searches a group of forwarding nodes that can maximize the network coverage, uneven node distribution and packet contentions or collisions may affect the performance.

V. Concluding Remarks

In this paper, we investigated pseudo geometric broadcast protocols and analyzed their performance in terms of packet delivery ratio, number of broadcasts, and propagation delay by changing the node density and network size. We proposed the EBP($|N_f|$) and NDS to maximize the network coverage while minimizing the number of broadcasts. For performance comparison, the AHBP is modified to work in WSNs. A variation of BPS, denoted as BPS*, is also modified and experimented. Extensive simulation results show that the proposed EBP($|N_f|$) and NDS achieve as high PDR as the AHBP and less number of broadcasts compared to other protocols. The AHBP shows the highest PDR and shortest propagation delay, but the largest and non-scalable number of broadcasts becomes an issue. The Approx and BPS* also show competitive performance. The performance analyses indicate that the proposed EBP($|N_f|$) and NDS can be a viable approach in resource constrained WSNs.

We plan to extend the proposed EBP($|N_f|$) and NDS and embed them into an energy harvesting WSN [13], where each node can adaptively change its communication range based on the availability of harvested energy from an environmental resource. In this paper, we implicitly assume that all nodes have the same communication range, but it may not be applicable in the network. We also plan to extend the EBP($|N_f|$) by adaptively changing the number of forwarding nodes ($|N_f|$) in the presence of time-varying node densities. This approach can also be applied to the NDS for reducing the computation overhead.

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