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Author(s)	Woon, W; Yeung, KL
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Variable Power Broadcasting Based on Local Information for Source-Dependent Broadcasting Protocols

Wilson Woon and Kwan L. Yeung
 Department of Electrical and Electronics Engineering,
 The University of Hong Kong,
 Pokfulam, Hong Kong
 Email: {thwoon, kyeung}@eee.hku.hk

Abstract—A typical broadcasting protocol for wireless network usually involves fixed transmission power that covers, for example an area within 250 meters (m). However, it is often unnecessary to broadcast using fixed power because a node that needs to be covered may just be 100m away. By reducing the transmission power enough to cover this node, energy expenditure would be reduced, thus, prolonging the lifetime of battery-powered wireless networks such as Mobile Ad Hoc Networks (MANETs) and Wireless Sensor Networks (WSNs). Existing source-dependent broadcasting protocols do not have any mechanisms for adjusting the transmission power of nodes. Therefore, this paper proposes some effective mechanisms based on local neighborhood knowledge, while ensuring the overall network is still covered. Results of extensive simulations confirm the effectiveness of the proposed protocols in reducing energy consumption.

I. INTRODUCTION

Network-wide broadcasting or simply referred to as broadcasting, is a way of disseminating information to all nodes in a network. It also plays an important role in establishing routes for on demand routing protocols [1], building routing tables for table-driven routing protocols [2], address assignment [3], and selecting nodes to form the backbone of a hierarchical network [4]. In a large network, due to the limited transmission power, a single broadcasting or transmission by a source node is usually insufficient to reach all nodes. In this case, the source node requires the assistance of its immediate neighbors to forward or rebroadcast the message to the nodes within their coverage area that have not received the information. This process continues until all nodes in the network received a copy of the information. An effective broadcasting protocol minimizes the number of nodes involved in forwarding or broadcasting a message. Any saved broadcasting could reduce packet collisions in a congested network, prolonging the lifetime of nodes that are battery powered, and lower channel utilization. In order to prolong the lifetime of a network more significantly, an effective broadcasting protocol should allow nodes to determine their most energy efficient transmission power so that the overall energy spent in disseminating a broadcast message is reduced without sacrificing reliability.

In this paper, we propose mechanisms that allow broadcast-ing nodes to select their most efficient transmission power so

that the overall energy consumption is reduced. More specifically, we implement these mechanisms on source-dependent broadcasting protocols [5-8]. These protocols require a broadcast-ing node to explicitly select a subset of its immediate neighbors (or 1-hop neighbors) to cover all its 2-hop neighbors. That is, before transmitting a message, a list of selected forwarding nodes' IDs is attached with the message. A node that receives the message will check if it has been selected as a forwarder. If yes (and its broadcast termination condition specified in the next section is not triggered), it will in turn select a set of forwarding nodes before rebroadcasting the message. Otherwise, it will discard the message. Notably, the transmission of messages involves fixed power and to the best of our knowledge, there is no mechanisms for adjusting the transmission power of broadcasting nodes available in source-dependent broadcasting protocols.

The motivation for varying the transmission power is simple. Assume nodes A and B are immediate neighbors of each other and their default transmission range (power) is fixed at 250m. However, the distance between nodes A and B is merely 50m away. Instead of sending at fixed power, node A should reduce its transmission range enough to cover node B. By reducing transmission power when necessary, the overall lifetime of the network can be prolonged.

In general, our proposed protocols consist of two phases. In the first phase, a broadcasting node uses existing source-dependent broadcasting protocols to select a set of forwarding nodes to cover all its 2-hop neighbors. Then, it adjusts its transmission power to reach its furthest forwarding node. In the second phase, the node determines whether its current forwarding nodes as well as transmission power are able to cover all its immediate neighbors. If yes, it continues to broadcast the message. Otherwise, it attempts to find additional forwarding nodes to reach those uncovered neighbors or simply extends its current transmission power to reach the furthest uncovered neighbor.

This rest of this paper is organized as follows. Section II critically reviews existing source-dependent broadcasting protocols and the broadcast termination conditions they adopted. In Section III, our proposed variable power broadcasting

protocols are presented, and their effectiveness is quantitatively studied in Section IV by simulations. Finally, Section V concludes the paper.

II. EXISTING SOURCE-DEPENDENT BROADCASTING PROTOCOLS

Without loss of generality, we assume that all nodes have knowledge of their 1-hop and 2-hop neighbors. This information can be obtained via periodic HELLO message exchanges. A HELLO message contains the identity of the sender as well as its 1-hop neighbors. Upon receiving the message, a node will treat the 1-hop neighbors of the sender as its 2-hop neighbors. The set of 1-hop and 2-hop neighbors of a particular node u are denoted as $N(u)$ and $N(N(u))$ respectively.

In the following, we first focus on the mechanisms for selecting forwarding nodes, where three deterministic broadcasting protocols, DP, TDP and PDP are reviewed. Then, the three broadcast termination conditions, *marked/unmarked*, *relayed/unrelayed*, and *covered/uncovered* are discussed. Note that termination condition is an integral part of a broadcasting protocol even though we present them separately below for clarity.

A. Dominant Pruning (DP) Protocol

The DP algorithm [6,7] is one of the earliest deterministic broadcasting protocols. In this algorithm, a node v that receives a broadcast message from source node u selects a minimum number of forwarding nodes from $N(v)$ to cover all nodes in $N(N(v))$. Among the nodes in $N(N(v))$, nodes in $N(u)$ have already received the message while nodes in $N(v)$ will receive it when node v rebroadcasts the message. Therefore, node v just need to select its forwarding nodes from the set $B(u, v) = N(v) - N(u)$ to cover all 2-hop neighbors in the set $U(u, v) = N(N(v)) - N(u) - N(v)$. The selection of forwarding nodes can follow the greedy algorithm in [6,7]. Firstly, a node in the set $B(u, v)$ is selected as a forwarder if it is the only node that can cover a node in the set $U(u, v)$. The process continues by repeatedly selecting nodes in $B(u, v)$ that can cover the maximum number of uncovered nodes in $U(u, v)$. In case of a tie, the node with the smallest ID is selected. Here, uncovered nodes refer to nodes that are not-yet-covered by a node in $B(u, v)$.

Assume nodes u and v are the source and a selected forwarding node respectively. The DP algorithm is summarized below:

- 1) Node v establishes the set $B(u, v)$ and $U(u, v)$ using $N(N(v))$, $N(u)$, and $N(v)$:

$$U(u, v) = N(N(v)) - N(u) - N(v)$$

$$B(u, v) = N(v) - N(u)$$

- 2) Node v then executes the greedy algorithm in [6,7] to select forwarding nodes from $B(u, v)$ to cover all nodes in $U(u, v)$.

B. Total Dominant Pruning (TDP) Protocol

TDP [5] further reduces the size of $U(u, v)$ by allowing node v to receive a message piggybacked with $N(N(u))$ from node u . Therefore, $U(u, v) = N(N(v)) - N(N(u))$ and $B(u, v) = N(v) - N(u)$. Similar to DP, the greedy algorithm [5] is adopted to select forwarding nodes from the set $B(u, v)$ to cover all nodes in $U(u, v)$. TDP is more effective than DP in reducing redundant broadcasting but it incurs additional overhead in piggybacking each data message with a list of 2-hop neighbors of the senders.

The TDP algorithm is summarized below:

- 1) Node v establishes the set $B(u, v)$ and $U(u, v)$ using $N(N(v))$ and $N(N(u))$:

$$U(u, v) = N(N(v)) - N(N(u))$$

$$B(u, v) = N(v) - N(u)$$

- 2) Node v then executes the greedy algorithm in [5] to select forwarding nodes from $B(u, v)$ to cover all nodes in $U(u, v)$.

C. Partial Dominant Pruning (PDP) Protocol

The approach taken by PDP algorithm does not require additional overhead, like TDP. Instead of just excluding nodes in $N(u)$ and $N(v)$ from the set $U(u, v)$, nodes in the set $P(u, v) = N(N(u) \cap N(v))$ can be excluded as well. Therefore, the 2-hop neighbor set to be covered is now reduced to $U(u, v) = N(N(v)) - N(u) - N(v) - P(u, v)$.

The PDP algorithm is summarized below:

- 1) Node v establishes the set $B(u, v)$ and $U(u, v)$ using $N(N(v))$, $N(u)$, $N(v)$, and $N(N(u) \cap N(v))$:

$$U(u, v) = N(N(v)) - N(u) - N(v) - N(N(u) \cap N(v))$$

$$B(u, v) = N(v) - N(u)$$

- 2) Node v then executes the greedy algorithm in [5] to select forwarding nodes from $B(u, v)$ to cover all nodes in $U(u, v)$.

The correctness of DP is given in [6,7] while TDP and PDP are given in [5]. A previous study [5] concludes that TDP and PDP algorithms are more effective in reducing redundant broadcasting compared with DP algorithm. The difference in number of transmitting nodes between TDP and PDP is marginal in most cases.

D. Broadcast Termination Conditions

Thus far, the discussion focuses on how to select forwarding nodes. In this section, we describe the broadcast termination conditions that govern whether a forwarding node should indeed rebroadcast a message as it is being asked for. Even though the process of selecting forwarding nodes is deterministic, the decision of whether to actually rebroadcast or not is based on a given termination condition. The effectiveness of

a broadcasting protocol in reducing redundant broadcasting is highly influenced by the termination condition used.

There are two termination conditions as proposed in [5]. The first one assigns a *marked/unmarked* status to each node. A forwarding node will rebroadcast a message only if there is at least one *unmarked* neighbor. Otherwise, the message is dropped. Initially, all nodes are *unmarked*. Upon receiving a broadcast message, a node will broadcast a control message “*marked*” to inform its neighbors regarding the change of its status. It is proven in [5] that if all the 1-hop neighbors of a selected forwarder have received the message (i.e. are *marked*), the selected forwarder does not need to rebroadcast the message because all its 2-hop neighbors have already been (or will be) covered by other broadcasting nodes. This *marked/unmarked* approach is very costly because it involves additional transmission of control messages. Moreover, this overhead could result in packet collisions in congested networks as well as additional energy consumption. Each node will also need to keep track of the status of each neighbor, thus making it an expensive mechanism.

The second termination condition assigns a *relayed/unrelayed* status to each node. When a node has *relayed* or forwarded a message, its status is changed from *unrelayed* to *relayed*. Unlike the *marked/unmarked* termination condition, there is no need to inform all neighbors about the change of status. A selected forwarding node will be inhibited from transmitting if its status is *relayed*. The correctness of this termination condition is trivial because if a node has broadcast the message before, then all its 1-hop and 2-hop neighbors have already been covered and further rebroadcasting of the same message is redundant. Compared with the *marked/unmarked* termination condition, the *relayed/unrelayed* approach is more applicable in a real network but as shown in [5], it is not very effective in ensuring minimum number of broadcasting nodes.

An additional termination condition, proposed in [8], assigns a *covered/uncovered* status to each node. Initially, all nodes are *uncovered*. When an *uncovered* node receives a message and it has not been selected as a forwarder by the sender, it becomes *covered*. When an *uncovered* node receives a message and it has been selected as a forwarder, it becomes *covered* **after** rebroadcasting the message. When a *covered* node receives a message, the message is dropped upon arrival. In other words, broadcast terminates at a *covered* node. The proof of correctness is given in [8]. As shown in [8], when applied to either DP, PDP, or TDP, this simple termination condition achieves significant savings in terms of number of broadcasting nodes.

As discussed previously, a termination condition determines whether a node selected for rebroadcasting should indeed rebroadcast a message or not. The DP protocol uses another “termination condition” when selecting forwarding nodes from the set $B(u, v)$. There is a possibility that a node in $U(u, v)$ may not be covered by any nodes in $B(u, v)$. Therefore, the DP protocol may get caught in a loop when executing step 2 of part A. In order to avoid this problem, a node should

“terminate” the greedy algorithm [5] (or step 2 of part A) whenever no new forwarding node is selected from $B(u, v)$. For the purpose of discussions and evaluations in the next sections, the DP, PDP, and TDP protocols will incorporate the *marked/unmarked* termination condition, while the protocols that use *covered/uncovered* termination condition are known as Enhanced DP (E-DP), E-PDP, and E-TDP.

III. PROPOSED VARIABLE TRANSMISSION POWER PROTOCOLS

We first present the energy model used in this paper. Without loss of generality, we assume a common channel model that follows the power law model [9]:

$$P_{recv} = \frac{P_{tx}}{r^n} \quad (1)$$

where P_{recv} is the strength (or power) of the signal when it arrives at a receiver, P_{tx} is the transmission power, r is the transmission range, and n is the power loss exponent that takes a value between 2 and 4. Each node is assigned a default maximum transmission power, P_{max} to send HELLO and *marked* messages. This value is included in the header of the HELLO message. In order to adjust the transmission power, each node needs to determine the transmission power that it needs to reach each of its neighbors. When a node receives a HELLO message from a neighbor, it simply extracts the power level with which the packet is transmitted (P_{max}) and compute the required transmission power, P_{req} , to reach this neighbor using the following equation:

$$P_{req} = \left[\frac{P_{max}}{P_{recv}} \right] \times P_{threshold} \quad (2)$$

where $P_{threshold}$ is the minimum power for a packet to be received correctly. Upon selecting a transmission power using one of our proposed mechanisms below, a broadcasting node will include it in the header of the broadcast message.

A. Enhanced PABLO (E-PABLO)

Our proposed Enhanced PABLO or E-PABLO was motivated by our previous work on Power Adaptive Broadcasting with Local Information (PABLO) protocol presented in [10]. It was developed specifically for self-pruning broadcasting protocols. Here, we extend it to source-dependent protocols.

In the first phase of E-PABLO, a broadcasting node, u , executes one of the greedy algorithms presented in Section II to select a set of forwarding nodes specifically to cover all its 2-hop neighbors. Node u then sets its transmission power to reach its furthest away forwarding node. When node u broadcasts a message using this transmission power, all its forwarding nodes as well as immediate neighbors that are within range will be covered. This will also ensure all its 2-hop neighbors are covered when the selected forwarding nodes rebroadcast. When node v receives a message from node u , its not-yet-covered neighbors are nodes in the set $N(N(v)) - N(u)$.

Using the current transmission power, not-yet-covered *immediate* neighbors of node u that are outside its range and not neighbors of *any* of its forwarding nodes will not be covered. Therefore, in the second phase, node u attempts to find additional forwarding nodes to cover these *unreachable* neighbors. The process of finding additional forwarding nodes is summarized in steps 10 to 16 of Algorithm 1. If node u cannot find any suitable forwarding nodes, it simply adjusts its transmission power to cover the furthest away *unreachable* neighbor and broadcasts the message.

The approach adopted by E-PABLO in finding additional forwarding nodes, i.e. steps 10 to 16, is based on the outside-in concept [12]. That is, the furthest away *unreachable* neighbor is evaluated first before considering nearer neighbors. The idea is to find a nearer neighbor as forwarding node to cover the furthest neighbor. Fig. 1 illustrates the outside-in concept. Note that this example is *independent* of Phase 1 and 3. In this example, the neighbors of node 10 in the set $N(10)$ includes nodes 9, 5, 0, and 3 where the furthest neighbor is node 9, followed by nodes 5, 0, and 3. The transmission power to reach nodes 9, 5, 0, and 3 is $P_{10,9} = 0.232021$, $P_{10,5} = 0.230102$, $P_{10,0} = 0.190218$, and $P_{10,3} = 0.103364$ respectively. Assume all neighbors of node 10 are *unreachable*. Since node 9 is the furthest *unreachable* neighbor, node 10 evaluates whether node 0 is a suitable relay node to node 9. Since $P_{10,0} + P_{0,9} < P_{10,9}$, node 10 will select node 0 as an *additional* forwarding node and removes node 9 from $X(10)$. The next furthest *unreachable* neighbor is node 5. However, node 3 cannot be used as a relay node because $P_{10,3} + P_{3,5} > P_{10,5}$. Therefore, node 10 sets its transmission power to $P_{10,5}$ or 0.230102.

At the end of phase 2, it is possible that a broadcasting node does not receive *marked* messages from all its neighbors. Fig. 2 illustrates one possible scenario. Assume nodes 5 and 43 select node 6 as their forwarding node using either DP, PDP, or TDP. Node 6 receives the first message from node 5 and based on steps 10 to 16 of Algorithm 1, it selects node 43 as its forwarding node to cover node 9. However, immediately after node 6 rebroadcasts the message, it receives the message from node 43. Since both nodes 6 and 43 already broadcast a message once, none of them will rebroadcast again to cover node 10. Therefore, in the optional phase 3, both nodes 6 and 43 will need to rebroadcast the message by setting their transmission power to reach node 10 due to the absence of a *marked* message from node 10.

Our proposed E-PABLO is summarized in Algorithm 1. We denote P_u and $P_{u,w}$ as the transmission power of node u and the transmission power that node u needs to use in order to reach a particular neighbor w respectively. The sets $F(u)$, $X(u)$, and $C(u)$ contain forwarding nodes, *unreachable* neighbors, and not-yet-covered immediate neighbors of node u respectively. To distinguish with the original broadcasting protocols presented in Section II, the DP, PDP, and TDP protocols with the *marked/unmarked* termination condition and E-PABLO are known as DP-PABLO, PDP-PABLO, and TDP-PABLO respectively.

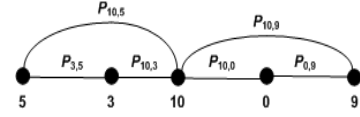


Fig. 1. A simple network to illustrate E-PABLO and E-INOP



Fig. 2. A simple network to illustrate the needs for Phase 3

B. Enhanced INOP (E-INOP)

Enhanced Inside-Out Power Adaptive Approach or E-INOP is another extension from our earlier work in [10]. E-INOP is summarized in Algorithm 2. While it is almost similar to E-PABLO, E-INOP has some variations in Phase 2. Notably, E-INOP starts from the nearest node and moves outward (inside-out) [11]. It considers the cumulative power to reach a node and covers all nodes up to this distance during broadcasting. Fig. 1 is again used for illustration of steps 10 to 22 of Algorithm 2. Similarly, this example is *independent* of Phase 1 and 3. In this example, we again assume all neighbors of node 10 are *unreachable* neighbors. Since node 3 is the nearest *unreachable* neighbor of node 10, the cumulative power to reach node 3 is $P_{10,3}^{cumu} = P_{10,3}$. If node 10 were to transmit using transmission power $P_{10,3}$, then neighbor 3 will be covered. Next, the cumulative power to reach the second furthest *unreachable* neighbor, that is node 0, is calculated as the minimum of (a) the power to reach node 0 directly from node 10 and (b) the sum of the cumulative power to reach the previous nearest *unreachable* neighbor, i.e. node 3, $P_{10,3}^{cumu}$, and the power to reach node 0 from a relay node. Since there is no relay node, the cumulative power now becomes $P_{10,0}^{cumu} = P_{10,0}$. The next nearest *unreachable* neighbor is node 5. Since $\min((P_{10,0}^{cumu} + P_{3,5}), P_{10,5})$ is $P_{10,5}$ the cumulative power to reach node 5 is $P_{10,5}^{cumu} = P_{10,5}$. The next neighbor is node 9. By evaluating $\min((P_{10,5}^{cumu} + P_{0,9}), P_{10,9})$, the cumulative power to reach node 9 is $P_{10,9}^{cumu} = P_{10,9}$. Finally, node 10 sets its transmission power to reach the furthest *unreachable* neighbor 9 or $P_{10,9}$. The DP, PDP, and TDP protocols with the *marked/unmarked* termination condition and E-INOP are known as DP-INOP, PDP-INOP, and TDP-INOP respectively.

C. Variable E-DP, E-PDP, and E-TDP

Notice that our proposed E-PABLO and E-INOP do not utilize the *covered/uncovered* broadcast termination condition. Recall that this termination condition does not involve any control messages. In the absence of ‘feedbacks’ from immediate neighbors, some nodes they were not selected as a forwarding node initially may somehow be selected by another node. In this case, the selection will be ignored, thus may result in uncovered nodes. Fig. 2 is reused for illustration. Assume node 6 receives the first message from node 5 and it selects

node 43 as its forwarding node. However, immediately after node 6 rebroadcasts the message, it receives a message from node 43. Since both nodes already broadcast a message once, none of them will rebroadcast again to cover node 10. Since node 10 does not send any acknowledgments, nodes 6 and 43 do not know that it is uncovered.

As alternatives, we propose Variable E-DP, E-PDP, and E-TDP or VE-DP, VE-PDP, and VE-TDP in this subsection. VE-DP, VE-PDP, and VE-TDP are simplified versions of the E-PABLO and E-INOP protocols that use the E-DP, E-PDP, and E-TDP broadcasting protocols. Firstly, a broadcasting node, u , selects a set of forwarding nodes to cover its 2-hop neighbors. Node u then adjusts its transmission power to cover furthest forwarding node. Then, it determines if *all* its not-yet-covered immediate neighbors are within its coverage. If not, it simply extends its transmission power to ensure the furthest not-yet-covered neighbor is covered. Notably, if node u is *covered*, it does not need to broadcast.

Phase 1

- 1) Establish $F(u)$ using either DP, PDP, or TDP
- 2) IF $F(u) = \emptyset$
- 3) For $a \in C(u)$, broadcast using P_{ua} , such that $P_{ua} \geq P_{ub} \forall b \in C(u)$
- 4) ELSE
- 5) For $f \in F(u)$, adjust $P_u = P_{uf}$, such that $P_{uf} \geq P_{ug} \forall g \in F(u)$

Phase 2

- 6) Store $\forall k \in C(u)$ into $X(u)$, such that $(P_{uk} > P_u)$ AND $k \notin N(f) \forall f \in F(u)$
- 7) IF $X(u) = \emptyset$
- 8) Broadcast using P_u
- 9) ELSE
- 10) Find $j \in X(u)$ such that $(P_{uj} \geq P_{ui}) \forall i \in X(u)$
- 11) Find $r \in N(u) - \{j\}$ such that $(P_{ur} + P_{rj}) \leq (P_{uq} + P_{qj}) \forall q \in N(u) - \{j\}$
- 12) IF $(P_{ur} + P_{rj}) < P_{uj}$
- 13) Eliminate j from $X(u)$
- 14) Add r into $F(u)$
- 15) ELSE
- 16) Broadcast using P_{uj}

Phase 3 (optional)

- 17) Find $m \in N(u)$ such that m does not send *marked* message AND $(P_{um} \geq P_{un}) \forall n \in N(u)$ that does not send *marked* message
- 18) Rebroadcast using P_{um}

Algorithm 1: Enhanced PABLO (E-PABLO)

IV. SIMULATIONS AND RESULTS

Extensive simulations are performed to evaluate the performance of all the protocols presented in Sections II and III in terms of number of broadcasting nodes and total energy consumption using NS2.34 [13]. The latter refers to energy consumed for transmitting data messages only and is the cumulative of the transmission power with which all data messages are sent. The maximum transmission power, P_{max}

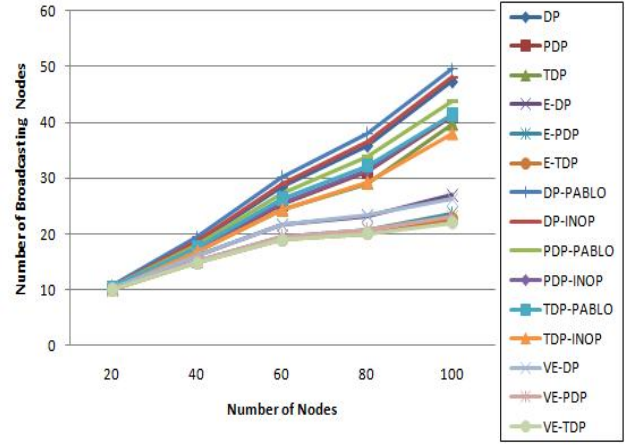


Fig. 3. Number of Broadcasting Nodes vs. Number of Nodes

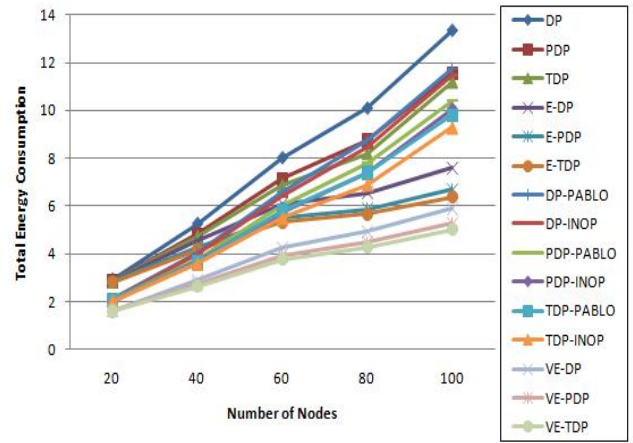


Fig. 4. Total Energy Consumption vs. Number of Nodes

is set to 0.2818384, which covers a range of 250m with the threshold power at the receiver $P_{threshold} = 3.652 \times 10^{-10}$, and the power loss exponent $n = 2$. The simulations are conducted in an ideal environment without channel contention, packet collisions, and nodes mobility that could change the overall network topology. In this environment, the packet size and channel bandwidth do not affect the simulation results. M number of nodes is randomly placed into an area of H m x H m and M is increased from 20 to 100 (step of 20) to see the effect of different node density. The value of H is set to 1000. For each combination of M and H , 20 different topologies are simulated and in each topology, every node takes turn to become the source node of a broadcast session. The network generator used ensures that each simulated topology is connected.

Figs. 3 and 4 show the number of broadcasting nodes and total energy consumption increases with the number of nodes. This is because as the number of nodes increases and spreads across the network, more broadcasting nodes are needed to ensure full coverage. This also leads to higher energy expenditure. From Fig. 4, we conclude that all our

proposed protocols are more effective than their original protocols in reducing energy consumption. However, as shown in Fig. 3, it comes at a cost of having more broadcasting nodes. For example, our proposed DP-PABLO protocol incurs energy savings of approximately 13% when compared with DP protocol in a network of 100 nodes. However, the number of broadcasting nodes increases by only about 4%. When comparing EDP-PABLO with E-DP using the same network, the saving is as significant as 22% while the increase in number of broadcasting nodes is merely 2.6%. This trend of relatively significant reduction in energy consumption and small increase in number of broadcasting nodes is observed for all other proposed protocols. Another notable observation is that INOP-based protocols are slightly more energy efficient and the number of broadcasting nodes is only marginally higher than PABLO-based protocols. This is inline with previous findings that INOP and its variants are more effective than PABLO-based protocols [10,11]. Finally, our proposed VE-TDP is the most energy efficient protocol mainly because it incurs the least number of broadcasting nodes.

V. CONCLUSION

To the best of our knowledge, existing source-dependent broadcasting protocols do not have any mechanisms to adjust the transmission power of nodes. Therefore, they are ineffective in cutting down unnecessary energy consumption especially in a battery-powered network. In this paper, we propose several algorithms that are effective in determining the most efficient transmission power for each broadcasting node. In general, our proposed protocols consists of two phases. In the first phase, we utilize the greedy algorithms adopted by current source-dependent broadcasting protocols to select a set of forwarding nodes to cover all 2-hop neighbors. The transmission power of a broadcasting node is adjusted to reach its furthest away forwarding node. However, immediate neighbors of the broadcasting node that are outside the transmission range and not neighbors of any forwarding nodes will not be covered. Therefore, in the second phase, a broadcasting node attempts to either adjusts its transmission power to reach the furthest away uncovered neighbor or find additional forwarding nodes to cover them. Results of extensive simulations presented in Section IV confirms the effectiveness of our proposed protocols.

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Phase 1

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- 5) For $f \in F(u)$, adjust $P_u = P_{uf}$, such that $P_{uf} \geq P_{ug} \forall g \in F(u)$

Phase 2

- 6) Store $\forall k \in C(u)$ into $X(u)$, such that $(P_{uk} > P_u)$ AND $k \notin N(f) \forall f \in F(u)$
- 7) IF $X(u) = \emptyset$
- 8) Broadcast using P_u
- 9) ELSE
- 10) Sort $X(u) = \{1, 2, 3, \dots, n\}$ such that $P_1 \leq P_2 \leq \dots \leq P_n$
- 11) $n = |X(u)|$, $F_{temp} = \emptyset$
- 12) for $(i = 1; i \leq n; i++)$
- 13) Let $R \subset N(u)$ such that $\forall q \in R, P_{uq} < P_{ui}$, $P_{qi} < P_{ui}$ and $P_{uq} \leq P_u$
- 14) IF $(R = \emptyset)$
- 15) $P_{ui}^{cumu} = P_{ui}$
- 16) ELSE
- 17) Find $r \in R$ such that $P_{ru} \leq P_{qi} \forall q \in R$
- 18) $P_{ui}^{cumu} = \min((P_{u(i-1)}^{cumu} + P_{ri}), P_{ui})$
- 19) $F_{temp} = F_{temp} \cup \{i\}$
- 20) Add $\forall r \in F_{temp}$ into $F(u)$ such that $P_{ur} \leq P_u$
- 21) Source u transmits with P_{ui} such that $i \geq j, \forall j \in F(u)$ AND $P_{ui} > P_u$. Otherwise, use P_u

Phase 3 (optional)

- 22) Find $m \in N(u)$ such that m does not send *marked* message AND $(P_{um} \geq P_{un}) \forall n \in N(u)$ that does not send *marked* message
- 23) Rebroadcast using P_{um}

Algorithm 2: Enhanced INOP (E-INOP)