

Adaptive Broadcast Cancellation Query Mechanism for Unstructured Networks

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Abstract—The availability of cheap wireless sensors boosted the emergence of unstructured networks using wireless technologies with decentralised administration. However, a simple task such as learning the temperature needs a discovery service to find a thermometer among all the sensors. In general, resource discovery relies on flooding mechanisms that waste energy and compromises system availability. Energy efficient strategies limit the exploration area, but with a significant impact on latency. The paper proposes ABC (Adaptive Broadcast Cancellation), a new algorithm that uses the knowledge acquired in previous discoveries to accelerate queries towards the resource. Knowledge is stored in a variation of Bloom filters, thus contributing for an efficient utilization of the sensors limited memory.

Keywords—Wireless Networks; Search; Broadcast; Cancellation.

I. INTRODUCTION

Many systems have been developed to monitor and locate resources in adverse places. An example are, mining and extraction companies which increasingly use wireless sensors to gather operating conditions data [1]. Low cost wireless sensors can be used to deploy an unstructured network in a mine, as it avoids extending copper wires over several kilometres while permitting to adapt the sampling rate and trigger alarms in a efficient way [2], [3].

Wireless Sensors Networks (WSNs) applications based on periodic reporting communication models [4], [5] are very inefficient in multi-hop networks because they are too resource-intensive (for memory, cpu, power) even when there is no new data to be transmitted. Unstructured sensor networks are developed to maintain communications when topology change, during removing and adding sensor nodes. When trying to locate some target resource, a node queries its neighbours. The simplest approach to implement a query is flooding, where the query is disseminated to all nodes. Unfortunately, successive flooding of the network consumes a lot of resources as it requires a large number of transmissions and occupies bandwidth, contributing to deplete the sensor nodes energy cells [6], [7], [3].

Some energy efficient search mechanisms aim to attenuate the negative impact of flooding by limiting the query scope [8], [9], [10]. This can be achieved by intentionally delaying propagation, exploring a trade-off between energy

consumption and response time. This paper proposes a new strategy to improve the performance of flooding protocols, by incorporating a distributed learning mechanism that adapts the protocol behaviour according to previously conducted queries. The paper shows that the proposed **Adaptive Broadcast Cancellation (ABC)** protocol can significantly improve latency and simultaneously reduce the number of retransmissions in long term scenarios, where queries are frequently repeated. ABC uses **Linear Bloom Filter (LBF)**, a Bloom filter inspired mechanism to store, propagate and compact the acquired information in the local vicinity. The ABC protocol was evaluated using the ns2 network simulation under several network scenarios. Evaluation shows that it is possible to speed up the searching tasks without compromising the energy efficiency.

II. RELATED WORK

One of the most simple and popular [8], [11], [12], [13] implementations of broadcast is known as flooding. Flooding is a very energy inefficient [14] mechanism where all nodes retransmit a message when it is received for the first time. One of the reasons for the inefficiency of flooding, comes from the continuation of the message propagation after the resource has been found.

Some solutions have been proposed to stop the flooding, when there is no need to continue the searching process. Limiting the flooding area by using geographically limited broadcasting [15], requires that nodes are aware of their and their peers location, what may not be possible in all scenarios. To control the query searching scope, without global location information, the Expanding Ring Search (ERS) [8] algorithm limits the query scope by adding a Time To Live (TTL) field to the message. Each intermediate node decrements the TTL when it forwards the query message and cease to forward it when TTL reaches 0. ERS works in rounds, if the resource was not found with some initial TTL, then another query is initiated and the TTL value is increased so that the query can go up to the following hops. This process is carried out until the initiator receives a successful answer. ERS will only be energy efficient when the resources are in the firsts hops. Other flooding based mechanisms limit the expanding query using geographical data or distance gradients. Unfortunately a comparison of these methods [15] shows they all exhibit a comparable performance. The Two-Sided Expanding Ring Search (TSERS) [6] considers a searching mechanism where

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two nodes are simultaneously executing the ERS for a path between each other. All intermediate nodes that receive a query can send back a successful response to the source of the query. TSERS explores the fact that searching cost is lower for shorter distances than for longer ones.

Solutions using chasing packets to stop the query propagation proved to be more energy-time efficient. In the Blocking Expanding Ring Search (BERS*) [16] and in some variations [17], [18], [19] a new control message was added to stop the retransmission process. When some resource is found an acknowledgement is sent back to the initiator node. The initiator sends the stop message, that is forward to every node and stops the expanding query. BERS family protocols are energy efficient when nodes wait a minimum time ($delay \leftarrow f(hop)$) before retransmission. During the delay time window, if a pending retransmission node receives a stop message, the node aborts the forward operation and the expanding query is blocked. However adding the minimum delay suitable for cancellation reduces the time efficiency. There is a trade-off between time efficiency and energy efficiency for protocols using chasing packets. More recent protocols such as Broadcast Cancellation Initiated from Resource (BCIR*) [10] and time-BERS (tBERS) [9], instead of waiting for the initiator node to start the cancellation process, start sending cancellation packets as soon as the resource is found. Both protocols improve time efficiency without additional energy costs.

Linear Bloom Filters (LBF), introduced in this paper, provide both a generalization of Bloom filters [20] and a simple approach to attenuate Bloom filters [21] to capture gradients of resources in a network [7]. The idea of using attenuated Bloom filters and directing routing towards resources is originally in [21]. Their design is based on a vector of standard binary Bloom filters data structures with a probabilistic document localization algorithm; by assigning different weights to each level, a metric similar to our *confidence* metric can be derived. Gradient-based routing using Bloom filters is also used in the Wader design [7]; here the strategy is to decay the information in the filter, by setting random bits to 0 as filters are transmitted, so that resources further away have a lower representation in the local filter. The LBF data structure is a modified Bloom filter capable to store the binary quantification of floating point values. The LBF uses just a single Bloom filter data structure instead of the multiple layered Bloom filters array used by the attenuated Bloom filter technique [21]. The LBF data structure controlled size makes ABC protocol independent of network diameter.

III. AN ADAPTIVE CANCELLATION MECHANISM

As discussed above, many broadcast cancellation protocols [16], [10] increase the delay linearly with hop distance. The increasing delay creates a time window to disseminate broadcasting cancellation messages, paving the way to minimize the number of retransmissions, at the expense of time efficiency. None of the protocols BERS* and BCIR* take advantage of the knowledge obtained with previous queries to improve the efficiency of the next. This section describes the **Adaptive Broadcast Cancellation (ABC)** protocol which, by assuming some topology stability, creates a gradient of resource locations that can improve the query dissemination. The ABC protocol abandons the blind delay increase by tuning

Algorithm 1: Linear Bloom Filter (LBF)

```

1  $lLBF[] \leftarrow [0, \dots, 0]$ ; // Local LBF
2  $att \leftarrow 0.9$ ; // Attenuation factor
3  $k \leftarrow 4$ ; // Number of hash functions
4 Function  $LBFFins(elem)$ 
5   for  $i \leftarrow 1$  to  $k$  do
6      $idx \leftarrow hash_i(elem)$ ;
7      $lLBF[idx] \leftarrow 1$ ;
8   end
9 Function  $LBFFmerge(rLBF[])$ 
10  for  $i \leftarrow 1$  to  $rLBF.size$  do
11     $lLBF[i] \leftarrow \max(lLBF[i], rLBF[i] \times att)$ ;
12  end
13 Function  $LBFFget(elem, lLBF[])$ 
14   $c \leftarrow 1$ ;
15  for  $i \leftarrow 1$  to  $k$  do
16     $idx \leftarrow hash_i(elem)$ ;
17     $c \leftarrow \min(c, lLBF[idx])$ ;
18  end
19  return  $c$ ;

```

it with the knowledge gained in previous queries. The key idea is to have nodes propagating queries faster in the direction where the resource is expected to be found. In contrast, when the relay by some node is assumed to be less relevant for a specific query, delay is kept at an adequate level to facilitate the cancellation process.

A. Linear Bloom Filter (LBF)

Knowledge about resource locations is abstracted by each node on a space-efficient probabilistic data structure coined as Linear Bloom Filter (LBF). A traditional Bloom filter is represented by a binary array where each position can store a bit $\{0, 1\}$, that is used to test whether an element is a member of a set or not. With the LBF variation of standard Bloom filters our approach stores floating point values $c \in [0, 1]$ instead of binary values. LBF assign a totality ordered confidence c quantity, to each stored element. This variation extends the traditional test operation, permitting to map each element in a set with a confidence c level, where 0 representing absence of knowledge and 1 the highest confidence. By default c is set to 0 for all LBF positions.

When a node hosts some resources, this information can be stored by setting c to 1 on the positions associated to the resources by the hash functions. In ABC, resources owned by neighbours are added to the same structure by editing the confidence values. Fig. 1 depicts an LBF sample representing the confidence values for elements $\{a, b, c, d, e\}$. By having all their positions with confidence 1, the LBF signals that elements $\{a, e\}$ are stored locally. The high confidence value associated to resource b suggest that it is stored in some node in the neighbourhood, while c and d are hosted by more distant nodes.



Fig. 1: Node context with LBF

LBF Operations: Alg. 1 defines three functions to operate the LBF data corresponding to the actions: i) inserting elements into a LBF; ii) merging data from two LBF; and iii) getting the

Algorithm 2: Start Query

```
1 begin
2   pkt ← creatPacket(...);
3   queryList ← queryList ∪ {msg.queryID};
4   pkt.bloom ← node.LLBF;
5   send(pkt);
6 end
```

confidence level for some element. Network resources are designated as $elem_i$ in LBF context. Function $LBFins(elem_i)$ is called to insert some $elem_i$ in node i 's LBF. It generates the hash keys to address k independent Bloom array positions, setting them to 1. Function $LBFmerge(rLLBF[])$ combines node i 's local information ($LLBF[]$) with received neighbour node information ($rLLBF[]$). Note that the remote data is attenuated by a constant factor att lower than 1, to privilege local information. Function $LBFget(elem_i, LLBF[])$ returns an estimate of the confidence value c assigned for element $elem_i$. The incorporation of the LBF gossiped in the query dissemination progressively attenuates the confidence values by att . A resource that is expected to be at hop distant, has a confidence level of $c = att^{hop}$.

B. Query Dissemination

To describe the ABC algorithm we assume that a node N_i can have three primitive actions related with each query: N_i can start a new query, by broadcasting a searching message m_s ; can start the cancellation process, by sending a cancellation message m_c or; N_i can forward either or both of the messages m_s and m_c . Network communication is asynchronous. Messages m_s and m_c are tagged with a $queryID$, so that N_i can track similar concurrent queries, avoiding message duplication and spurious retransmissions on the WSN.

Before broadcasting the first query there is no network context and each N_i only knows its local resources ($LLBF[]$). However it will be necessary to disseminate the local context through the network, without knowing the number of nodes or topological properties, such as network diameter.

When N_i starts a new query it creates a new packet as illustrated in Alg. 2. A query is initiated with the broadcast of a message m_s . N_i copies $LLBF[]$ into the message header, thus initiating its dissemination. To acquire resource context the $LLBF[]$ is piggybacked in the message and incorporated in the LBFs of the receiving nodes, using function $LBFmerge(rLLBF[])$. Learning with a piggybacking approach prevents the dissemination of additional messages. The increase in the size of the payload is not significant and is bounded to the LBF size.

C. Query Handling

As in BCIR* [10], ABC progressively increases query propagation latency to facilitate the dissemination of cancellation messages once the resource is found. This is reflected in the query handling algorithm depicted in Alg. 3. Once a query is received, nodes confirm message validity, discarding it if i) a cancellation for this message was already received or ii) it is a duplicate. Afterwards, the query may produce two outcomes. The node either starts the cancellation process by

Algorithm 3: Query Handling

```
1 Function handleQuery (msg)
2   LBFmerge(msg.rLLBF);
3   pkt.bloom ← node.LLBF;
4   if msg.queryID ∉ queryList then
5     queryList ← queryList ∪ {msg.queryID};
6     if LBFget(msg.elem, LLBF) = 1.0 then
7       cancelList ← cancelList ∪ {msg.queryID};
8       send(CancelPacket(pkt));
9     else
10      time ← calcDelay(msg.header, ABC);
11      insertTxQueue(time, pkt);
12    end
13  end
14 Function handleCancellation(msg)
15   LBFmerge(msg.rLLBF);
16   pkt.bloom ← node.LLBF;
17   if IsInTxQueue(pkt) then
18     removeTxQueue(pkt);
19   else
20     if (NodeHostsResource(msg.elem) ∧
21        node.resourceFound[msg.queryID] = False) then
22       node.resourceFound[msg.queryID] ← True;
23       msg.resourceHost[msg.queryID] ← node.ID;
24     end
25     if msg.queryID ∉ cancelList ∧
26        msg.queryID ∈ queryList then
27       time ← calcDelay(msg.header, FLOOD);
28       insertTxQueue(time, pkt);
29     end
30     cancelList ← cancelList ∪ {msg.queryID};
31  end
```

Algorithm 4: Added delay

```
1 const DELAY_MIN ; // Minimum delay
2 const JIT_MAX ; // Maximum jitter
3 Function calcDelay (msg,proto)
4   jitter ← runif(0, JIT_MAX); // Random Uniform
5   timeFLOOD ← DELAY_MIN + jitter;
6   timeBCIR* ←
7     max(2 · (msg.hop - 1) · timeFLOOD, timeFLOOD);
8   c1 ← LBFget(msg.elem, msg.rLLBF);
9   c2 ← LBFget(msg.elem, node.LLBF);
10  if c1 < c2 then
11    timeABC ← max(2 · (msg.hop - 1) · DELAY_MIN ·
12      (1 - c2) + jitter, timeFLOOD);
13  else
14    timeABC ← timeBCIR*;
15  end
16  return now() + time_proto;
```

sending m_c if it hosts the corresponding resource, or schedule the query message m_s for retransmission.

The ABC added delay applied during the query dissemination follows Alg. 4 and considers 3 components. The resource location independent component is given by a static value (DELAY_MIN) plus some $jitter$, modelled by a random uniform distribution. The location dependent component makes the delay proportional to the message hop counter (see Alg. 3). This is the component that facilitates message cancellation. The third component is dictated by the nodes estimation of its distance to the resource, given by the LBF prediction. This component given by $(1 - c_2)$ (see Alg. 4) aims to speed up the query propagation in the predicted direction of the node hosting the resource. The $calcDelay(msg, proto)$ function in Alg. 4 returns the schedule time for message retransmission.

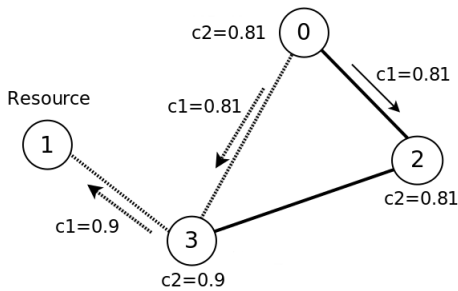


Fig. 2: ABC - Delay Attenuation

Fig. 2 depicts an example of a query propagation accelerated into the most likely direction. It considers that N_0 starts looking for a resource located at N_1 and assumes that nodes know the confidence c associated with the expected hop distance. N_3 receives m_s and given that $c_1 < c_2$, an attenuation $(1 - c_2)$ is applied to the delay, speeding up the query towards node N_1 . On the other hand, given that N_2 receives m_s and $c_1 \geq c_2$, no attenuation will be applied.

IV. EVALUATION

Ad-hoc network topologies can be modelled using Random Geometric Graphs (RGG) or approached by synthetic topologies, such as those of the Manhattan movement model. This paper evaluates both of these topology classes, while examining some more extreme deployments, occurring in mines [1], that exhibit higher path lengths. To evaluate the performance of ABC and understand the impact of the adaptive delay on the number of transmissions and end-to-end delay, an implementation for the ns2 network simulation was developed. ABC is compared with a naive implementation using plain flooding and BCIR*, that one of the most efficient protocols to control the query searching scope. ABC includes the adaptive delay while other broadcast cancellation protocols operate without knowledge from previous queries.

Two metrics are used to study the ABC time and energy efficiency behaviour, namely end-to-end delay and the number of transmissions. The **end-to-end delay (L)** is defined as the average time between the broadcasting search by the initiator node N_0 and the moment at which N_0 receives the first answer. The energy cost is measured by the average **number of transmissions (R)** performed by every node on each query. It is assumed that any two retransmissions consume the same amount of energy.

A. Network Topologies

Two topology models are used to create Manhattan scenarios for ns2. The Manhattan scenarios are set up with equidistant streets from each other, ensuring that the interior streets share equitably distance to cover the area. The distance between the streets is greater than the radio range, to avoid direct communication from one street to another. The **equidistant grid** was generated with 176 nodes uniformly distributed along the rows covering an area of $3200 \times 3200m^2$, resulting in a node density of ≈ 17 Nodes/Km². The **Manhattan** topology was generated using the BonnMotion¹ tool with 250 nodes

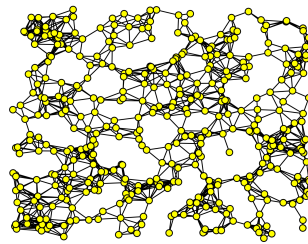


Fig. 3: Random Geometric Graph ($N \approx 400$)

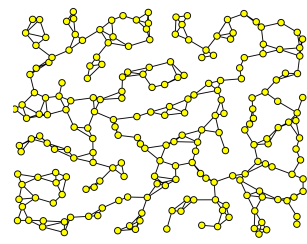


Fig. 4: *Modified* Random Geometric Graph ($N \approx 165$)

TABLE I: ns2 Simulation Parameters

| Attribute | Value [Default] |
|-----------------------|-----------------|
| DELAY_MIN | 10 ms |
| jitter | 7 ms |
| Packet Size | 1000 bytes |
| Max Simulation Time | 17000s |
| Number of topologies | 500 |
| Radio range | 250 m |
| Network links | 11 MBit/s |
| Transmission power | 25 dBm |
| Antenna gain | 1 |
| Antenna Polarization | Omnidirectional |
| ns2 propagation model | TwoRayGround |

distributed along the streets covering an area of $2000 \times 2500m^2$, resulting in a node density of 50 Nodes/Km².

The creation of the **mine topologies** mirrors previous works [22] [23] using random geometric graphs (RGG) to model wireless networks topologies. The bi-dimensional random geometric graph model $G(N, r, \ell)$ creates N nodes that are randomly placed inside a unit square area. The topology defined in the unit square is mapped into the ns2 using a linear transformation taking into account the radio transmission range. Any two nodes whose euclidean distance is below r are considered connected and linked by an edge. Unfortunately the RGGs created using NetworkX² reveal a graph topology that was not suitable to represent mine topologies scenarios because there were too many clusters with high level of redundancy. To create more realistic scenarios, a maximum graph degree was defined by removing nodes whose degree exceeds a threshold. The result is a *modified* random geometric graph. Figure 3 depicts the original RGG as created by NetworkX and Figure 4 depicts the modified version of the same graph, after imposing a limit to the node degree. The mine topologies use $N \approx 165$ nodes on a square area of $3100 \times 3100m^2$.

The modified RGG is considered to make a better mine structure representation, resulting in a topology with longer paths (tunnels) and lower node density.

B. Experiment Setup

Table I summarizes the parameters used for setting ns2 simulations. The antenna settings, signal power and receiving threshold, are selected to give approximately 250m of radio communication range. To each node is attached one resource. The queries are schedule in random order and search for random resources.

¹<http://sys.cs.uos.de/bonnmotion/index.shtml>

²<http://networkx.github.io>

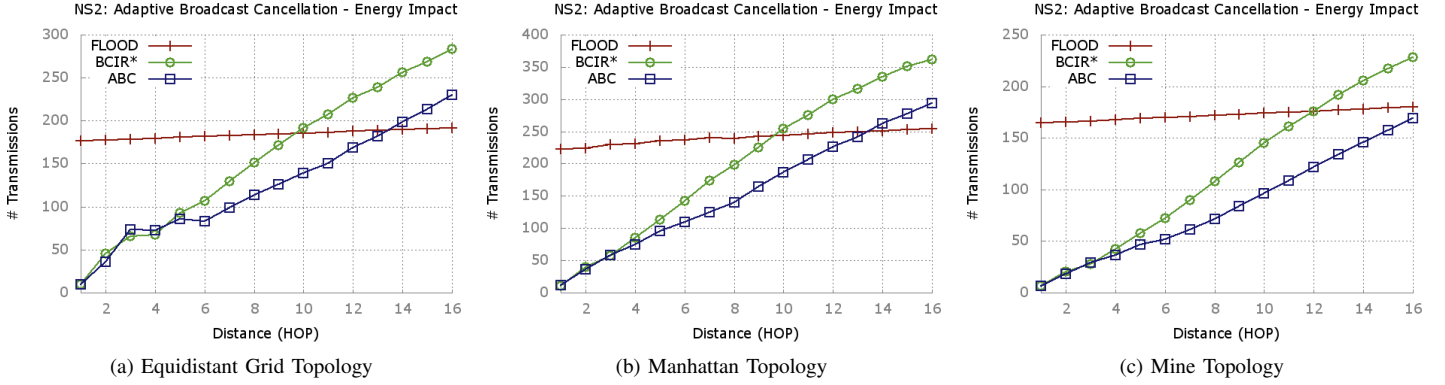


Fig. 5: Impact of the topologies and distance on the number of transmissions.

The ABC evaluation tests use a default LBF with $m = 256$ cells and $k = 4$ hash functions. These constants are suggested by Eq. (1), extracted from [7], to provide a false positive probability up to $fp = 5\%$ and considering that LBF can keep information for at least 40 resources (i.e. $\#LBF < 40$).

$$m = -\frac{\#LBF \cdot \ln(fp)}{(\ln 2)^2} \quad ; \quad k = \ln(2) \cdot \frac{m}{\#LBF} \quad (1)$$

The attenuation factor att (used in Algorithm 1) can be any value from $[0, 1]$ and is set to $att = 0,9$ corresponding to 10% of attenuation for each hop.

C. Result Analysis

Results are presented as a function of the distance between the initiator and the first node responding with a successful answer, a metric hereafter designated as hop count.

All protocols are submitted to a pool of 500 topologies. For each topology, the queries are scheduled using a uniform distribution over the maximum simulation time. The absolute number of queries that received a successful reply is depicted in Fig. 7. Table II lists the percentage of packet drops for each protocol, which confirms density and topology impact on the algorithms performance. Not surprisingly, for the equidistant grid and Manhattan topologies, the number of packets dropped increases with node density, an aspect that can be attributed to the increasing number of collisions.

TABLE II: Packet Drops

| TOPOLOGY | Nodes/Km ² | FLOOD | BCIR* | ABC |
|------------------|-----------------------|-------|-------|-------|
| Mine | ≈ 17 | ≈ 5% | ≈ 3% | ≈ 3% |
| Equidistant Grid | ≈ 17 | ≈ 11% | ≈ 10% | ≈ 10% |
| Manhattan | ≈ 50 | ≈ 30% | ≈ 32% | ≈ 33% |

The impact of packet drops can be observed in Fig. 7, which shows the absolute number of successfully replied queries in the mine scenario. A comparison with table II suggests a correlation between the number of successfully queries and the number of packets dropped.

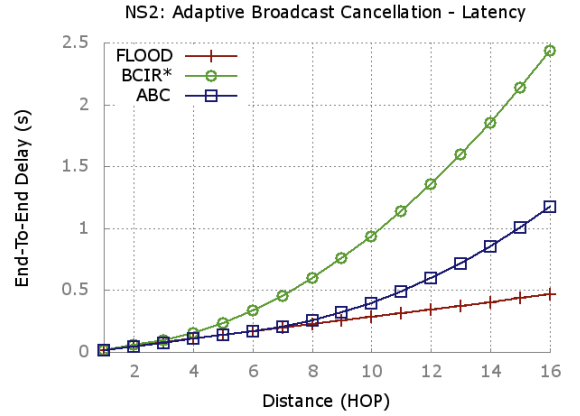


Fig. 6: End-To-End Delay

Energy impact. Assuming that transmissions are the dominant factor on energy consumption in a system based on wireless communications, we compare the energy efficiency by counting the number of transmissions used until all messages related with a query cease to be propagated. As depicted in Fig. 5, the energy consumption of ABC is smaller than BCIR* for queries to resources at 6 or more hops. A comparison between the mine and the equidistant grid topologies shows that the adaptation mechanism of ABC preserves the energy consumption in a pattern comparable to BCIR*, specially in the first hops. This is very significant considering that ABC was able to improve latency and that BCIR* is capable of significantly reducing transmissions with respect to flooding.

Latency. Fig. 6 shows the variation of the average end-to-end delay between the moment a query is broadcast and its sender receives a reply. The ABC protocol significantly reduces the average end-to-end time and the gains increase with the distance to the resource (Fig. 6). For example, the difference between BCIR* and the FLOOD baseline for $H = 4$ is similar to the difference between ABC and the FLOOD baseline for $H = 8$. This result can be attributed to the LBF contribution for accelerating the query propagation in the resource direction, a unique property of ABC which makes it competitive with flooding for resources located up to 7 hops.

Both ABC and BCIR* protocols evidenced a trade-off between latency and the number of transmissions, and by

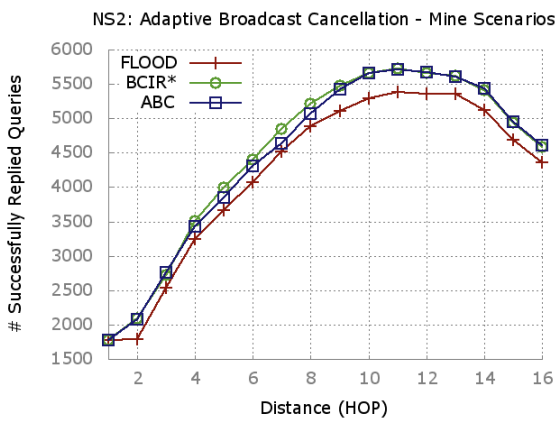


Fig. 7: Successfully Replied Queries (Mine Scenarios)

comparing the performance for resources at the same distance, ABC significant gains in time with faster responses and with a reduction in the number of transmissions. The gains increase in line with the distance between the source of query and the resource. However, a cross-analysis of Fig. 5 and Fig. 6 indicate that ABC is able to reduce the latency without increasing transmissions cost.

Fig. 7 shows that the number of successfully replied queries for ABC is similar to BCIR* and by combining with the latency information from Fig. 6, the results show a very significant reduction in latency, justifying the effort to reduce the added delay achieved by ABC.

V. CONCLUSIONS

Mechanisms to improve the performance of resource discovery in WSNs typically exhibit a trade-off between the number of transmissions and latency. This paper presented ABC, an algorithm that makes an innovative approach capable to attenuate such trade-off by speeding the query propagation in the predicted direction of the resource. Evaluation showed that a sense of the resource location can significantly reduce the end-to-end time, while still benefiting from a reduction in energy cost for successive discovery queries. ABC achieves these goals with a small penalty in the query message size, resulting from the piggyback LBFs inside query messages. The ABC protocol operates by taking advantage of the query propagation mechanism, to epidemically disseminates the resource location direction without increasing the number of transmitted messages.

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