A TWO-HOP ACK SCHEME FOR ENSURING SURVIVABILITY IN A COOPERATIVE TRANSMISSION NETWORK

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***Abstract*— In this paper we propose a new acknowledgement scheme for a wireless sensor network that uses opportunistic large arrays (OLAs). An OLA is a simple type of cooperative transmission in which simple, inexpensive relays or forwarding nodes operate without any mutual coordination, but naturally fire together in response to energy received from a single source or another OLA. By addressing node clusters rather than individual nodes, the Two-Hop ACK detects a network partition caused by a hole or cluster of node failures that would block one hop. The proposed OLA size adaptation mechanism implicitly triggers the creation of a large enough OLA to straddle such holes during the forwarding process. The two-hop ACK is explained in the context of the OLA Concentric Routing Algorithm with flooding and threshold (OLACRA-FT), which is a robust version of the OLACRA protocol. The proposed ACK scheme requires no centralized control and does not require that nodes know their locations. The two-hop ACK scheme uses orthogonal preamble decoding to enable a node to decode necessary information even when an overheard transmission collides with other, intentional transmissions.**

***Keywords*—Opportunistic Large Array, Cooperative Diversity, Partitioning, Wireless Multi-hop Networks, Topology, Disconnected Networks, Node failure, Wireless Sensor Network, Sensor Holes.**

1. INTRODUCTION

Network survivability, a critical function in any wireless sensor network (WSN), concerns the maintenance of the communication infrastructure when nodes are blocked, disabled or destroyed [1]. Lately, a particularly simple and energy-efficient form of cooperative transmission, the opportunistic large array (OLA), has been proposed for broadcasting in WSNs [3]. An opportunistic large array (OLA) is a form of cooperative diversity in which large groups of simple, inexpensive relays or forwarding nodes operate without any mutual coordination, but naturally fire together in response to energy received from a single source or another OLA. The OLA Concentric Routing Algorithm with flooding and threshold (OLACRA-FT), proposed for upstream routing using OLAs, takes advantage of the concentric ring structure of the broadcast OLAs to limit flooding on the upstream. OLACRA-FT has been shown to save over 75% of the energy in compared to OLA based flood have been proposed for upstream routing using OLAs [2]. Both OLA and OLACRA-FT avoid addressing individual nodes, which makes them scalable with network density. In this paper, we introduce an ACK protocol for OLA and OLACRA-FT. The ACK Protocol will detect a cluster of disabled nodes that would block one hop, and remedy the situation by growing the OLA around the cluster. *Orthogonal preamble encoding* that has been proposed by others for determining multiplicity of collisions in retransmission diversity [4] is used in the proposed ACK protocol to enable critical control information to be decoded when uplink and downlink packets collide.

To the best knowledge of the authors, there have been no works yet that treat survivability for OLA based networks. The paper presents a two-hop ACK protocol that overcomes a 'hole' in the network that could be caused by a cluster of node failures or a large object blocking transmission. The protocol will be explained in the context of OLACRA-FT.

II. NETWORK MODEL

Half-duplex nodes are assumed to be distributed uniformly and randomly over a continuous area with average density ρ. For simplicity of analysis, the '*deterministic model*' [3] is assumed, which implies node transmissions are orthogonal. However, OLACRA has been shown to work in non-orthogonal fading channels as well [5].

We assume a node can "decode and forward" (D&F) a message without error when its received signal-to-noise ratio (SNR) is greater than or equal to a modulation-dependent threshold τ_d. Let the source power be P_s and the relay transmit power per unit area be denoted $\overline{P}_r$. For a fixed $\overline{P}_r$, there exists a maximum threshold value such that the relayed signal will be propagated in a sustained manner by concentric OLAs [3]. Borders of such downstream OLAs are illustrated by dashed circles in Fig. 1.a, where the nodes are grey dots and the sink is in the center.

III. DESCRIPTION OF OLACRA

OLACRA depends on an 'initialization phase' to help nodes decide if they should relay an upstream transmission or not. In this phase, the sink transmits with waveforms or preambles W_1 with power P_{sink}. "Downstream Level 1" or DL^1 nodes are those that can D&F the sink transmission. Only those DL^1 nodes whose received SNR is less than a specified transmission threshold τ_b retransmit using a different waveform W_2. The constraint on SNR is done to prevent nodes near the *rear boundary* in a level from transmitting, to save energy [2]. The difference between τ_b and τ_d is defined to be epsilon, ε. Sensor nodes that can D&F the signal at W_2, and which have not relayed this message before join DL^2. DL^2

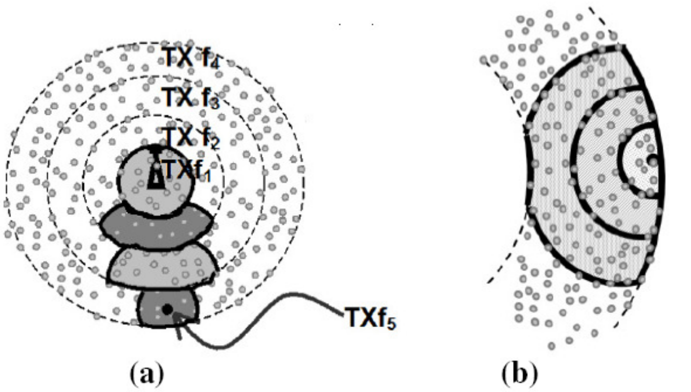

Fig.1 (a) OLA broadcast rings (dotted circles) and OLACRA-FT OLAs(shaded regions) (b) UL^{1} flood levels

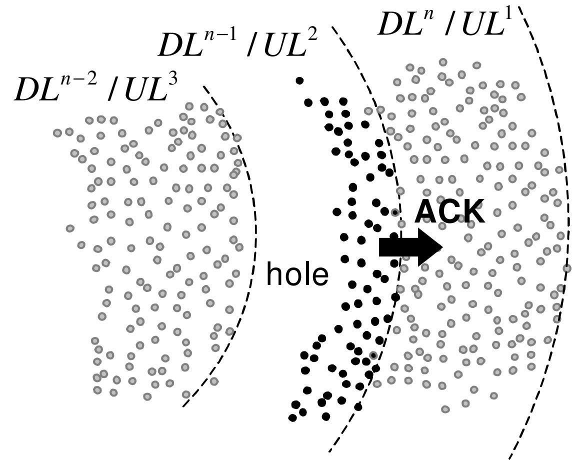

Fig 2. Single Hop ACK Scheme

nodes whose received SNR is less τ_b then retransmit using a different waveform W_3. This continues until each node is indexed with a particular level. A level in OLA network is analogous to a hop in the multihop network.

For upstream communication, a source node in DL^{n-1} transmits using W_n. Any node, that can D&F at W_n will repeat at W_{n-1} *if it is identified with* DL^{n-1}, it has not repeated the message before and the received SNR is less than the transmission threshold. . We shall refer to the n^{th} upstream OLA as UL^{n}, where UL^{1} contains the source. In Fig. 1.a for example, UL^{1} is indicated by the outermost shaded shape and UL^{4} contains the sink in the middle of the network. The *forward boundary* of UL^{n} divides the nodes of UL^{n} from those that are eligible to be in UL^{n+1}. OLA flooding is done in just the first upstream level until an OLA meets the upstream forward boundary of DL^{n} to enhance upstream connectivity as shown in Fig.1.b [2].

IV. OLACRA TWO HOP ACK SCHEME

Single Hop ACK Schemes might not be sufficient to ensure the receipt of message by all the nodes in the subsequent hop/level for OLA networks as a 'hop' in an OLA network is no longer a single node but a collection of nodes. For example in Fig. 2, suppose the upstream source is in DL^{n} and there is a *hole* in DL^{n-1}. All nodes in DL^{n} would still receive an ACK from the nodes, shown as black dots in the figure, in the DL^{n-1} forward boundary, but the message doesn't get to DL^{n-2} because of the network hole in DL^{n-1}.

The Two-hop ACK uses the following control messages.

1) VACK (Virtual ACK) is simply the OLA transmission that is decoded by nodes in the downstream direction because of omni-directional antennas, even though the signal is intended to travel upstream.
2) RACK (Real ACK) is a very short message intended for the downstream direction. RACK is the ACK sent by nodes in DL^{n-1} to nodes in DL^{n}, which indicates that the DL^{n-1} nodes have decoded the VACK from DL^{n-2} .
3) VRACK (Virtual RACK) is the RACK intended for DL^{n}, but decoded by nodes in DL^{n-2}.
4) RREQ (Retransmission request): Nodes in DL^{n} that transmitted the original message but did not receive the RACK for it, will transmit the short control message RREQ.
5) ReTx: DL^{n-1} nodes that decoded the original message and RREQ transmit ReTx to recruit more nodes from the same level. ReTx includes the original data payload.

A. Timing Diagrams

Fig.3 shows the timing diagrams for the Two Hop ACK Scheme. The vertical axis indicates time slots and the horizontal axis shows the downstream levels. For example T4 at DL^{n} in Fig.3.a shows the activities of DL^{n} nodes in the fourth time interval. The different messages are color- and line-coded as shown in the legend. Fig 3.a and 3.b show operation without and with a hole respectively.

In Fig3.a at T1, nodes in DL^{n} transmit the upstream message. Nodes in DL^{n-1} that can decode this transmission relay at T2. Nodes in DL^{n} also decode this transmission and note the receipt of their VACK. Likewise when nodes in DL^{n-2} relay at T3, nodes in DL^{n-1} will note the receipt of their VACK. DL^{n-1} nodes that can decode the VACK transmit the RACK at T4. Therefore, a node in DL^{n} that decodes a RACK knows that the message was decoded by at least one node in DL^{n-2} and therefore the message must have made it past DL^{n-1}. However nodes in DL^{n} that do not decode the

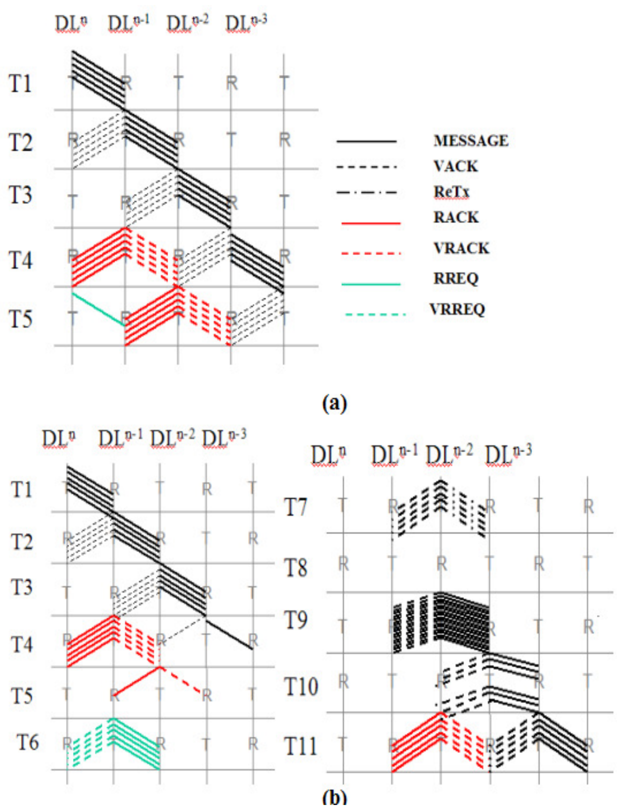

Figure 3. (a) The Two-Hop ACK Scheme when there is no hole. (b) The scheme when there is a hole in DL^{n-3}.

RACK transmit a RREQ at T5. Nodes in DL^{n-1} that hear RREQ and RACK from DL^{n-2} simultaneously, ignore the RREQ and decode RACK since RACK is a higher-level acknowledgement.

Fig 3.b shows the case when there is a network hole in DL^{n-3} and illustrates the *OLA Size adaptation mechanism*. Transmissions progress in the same way as in Fig 3.a until T3. At T4 only very few nodes in DL^{n-3} relay the message because of the hole, hence very few nodes in DL^{n-2} decode the VACK and transmit RACK. Therefore a large number of nodes in DL^{n-1} do not decode the RACK and will transmit RREQ at T6. In this case, DL^{n-2} nodes receiving RREQ without a higher level RACK transmit ReTx at T7 (they received this message back in T2). It is necessary that nodes that do not have something to transmit be in the receiving mode even though the time-slot is labelled 'T' so that they hear the RREQ. ReTx transmission at T7 is intended to recruit more nodes from the same level to relay the message so that the next OLA can go around the hole thereby maintaining connectivity. Then in T9, all nodes in DL^{n-2} that ever decoded the original message (at T2 or T7) transmit together as an enlarged OLA. Finally, in T10, additional

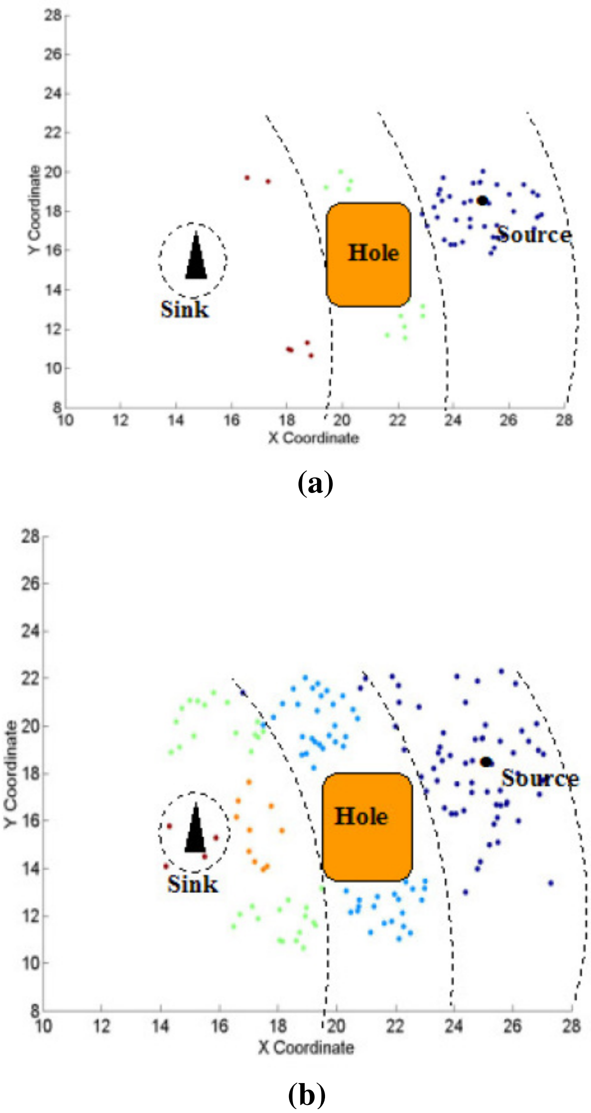

Figure 6. (a) transmissions die off (b) the network readjusts itself using the Two Hop ACK Timing Scheme and goes around the hole

nodes in DL^{n-3} are able to decode the message, and the hole is overcome.

B. Design for Orthogonal Preamble Decoding

We note in Fig 3.a that at T4 DL^{n-1} nodes hear VACK from DL^{n-2} and VRACK from DL^{n}. If not carefully designed these two signals would collide and the nodes wouldn't be able to decode the required signal, VACK in this case. *Orthogonal preamble encoding* can enable the retrieval of control information when a node experiences this kind of collision. We identify two types of collisions that can occur in the ACK scheme,

- Type 1 – V-RACK and VACK for the same payload ID as seen in Fig. 3.a at T4 in DL^{n-2}. VACK must be separately detected, regardless of the presence of V-RACK. Therefore V-RACK and VACK preambles are designed to be orthogonal.
- Type 2 – RACK and RREQ for the same payload ID, as shown in Fig.3.a at T5, DL^{n-1}. Here RACK must be separately detected regardlesss of the presence of RREQ. Therefore, the RACK and RREQ symbols are designed to be orthogonal.

V. RESULTS

Normalized power and distance variables were used. 2000 nodes were randomly distributed in a circular field of diameter 30 with the Sink located at the center at (15,15). The Upstream source was located at a radius 11 at (25,19). The downlink was established using with $P_s = 3$ and $\bar{P}_r = 1.1$ and the upstream had $P_s = 1.5$ and $\bar{P}_r = 2$. $\tau_d = 1$ for upstream and downstream. Fixed ε values of 1.5 and 2 was used downstream and upstream, respectively. The rectangular hole had width 2 and height 5 and was centered at (22,15.5). Fig. 6 shows the nodes that decoded the transmission. In Fig 6.a the transmissions die off before getting to the Sink. In Fig 6.b Two Hop ACK Timing Scheme was employed and the nodes detect the presence of the hole. The protocol recruits more nodes from UL^1 and the transmissions go around the hole ensuring connectivity.

VI. CONCLUSION

An OLA-based solution to address the survivability issue in a WSN is considered. The proposed Two-Hop ACK Scheme has been shown to overcome network holes without requiring individual node addressing or centralized control.

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