

A Proposal for Network Coding with the IEEE 802.15.6 Standard

Xiaomeng Shi and Muriel Médard

*Department of Electrical Engineering and Computer Science,
Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA, U.S.A.*

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Abstract: We examine the Medium Access Control sublayer of the IEEE 802.15.6 Wireless Body Area Network (WBAN) standard, and propose minor modifications to the standard so that linear random network coding can be included to help improve energy efficiency and throughput of WBANs compatible with the standard. Both generation-based and sliding window approaches are possible, and a group-block acknowledgment scheme can be implemented by modifying block acknowledgment control type frames. Discussions on potential energy and throughput advantages of network coding are provided.

1 INTRODUCTION

The IEEE 802.15.6 WBAN standard (IEEE, 2012) was published by the IEEE 802.15 Task Group 6 (TG6) in 2012 to overcome limitations of other Personal Area Network standards such as IEEE 802.15.4 (Zigbee) and IEEE 802.15.1 (Bluetooth). Since its initial draft proposal, many studies have been conducted to analyze the performance of medium access mechanisms of this standard. For example, (Ullah and Kwak, 2011) presents theoretical throughput and delay limits and bandwidth efficiency results for ideal channels without transmission errors, while (Tachtatzis et al., 2010) analyzes the energy lifetime of periodic scheduled access modes.

In this article, we propose to incorporate the use of network coding (NC) into a WBAN arranged in a star topology. By examining the IEEE 802.15.6 standard, we propose modifications to frame acknowledgment schemes so that linear NC can be included in the communication process, thus potentially improve the energy efficiency and/or throughput of the system.

Although still a relatively young field, NC has shown great potential in addressing issues such as network throughput, robustness, and security (Fragouli and Soljanin, 2007). Unlike traditional routing, NC encourages nodes within a network to mix data before forwarding. Data flows are viewed as information which can be combined algebraically. As long as enough degrees of freedom, in the form of linearly independent coded packets or symbols, are received, the original uncoded data can be recovered.

The concept of NC is introduced in the seminal paper (Ahlsweide et al., 2000). The authors in (Koetter and Médard, 2003) provide an algebraic framework for linear network codes, while (Ho et al., 2006) introduces random linear network codes (RLNC), showing that RLNC achieves multicast capacity probabilistically in a distributed manner, exponentially in the finite field size for coding operations. Several practical approaches of NC have since been proposed to bridge theoretical studies to real applications. To take into account randomly generated coding coefficients, a generation-based scheme with concurrently transmitted coefficients is considered in (Chou et al., 2003) to allow NC to co-exist with current network protocols. Simple XOR codes can be implemented in two-way relay networks and four-way cross topologies by inserting an additional NC layer between the IP and MAC layers of the 802.11 protocol (Katti et al., 2008). Apart from such generation-based schemes, a sliding-window approach similar to that used in the Transmission Control Protocol (TCP) for flow and congestion control can be introduced for NC, such that end-to-end packet losses in wireless networks using TCP can be masked (Sundararajan et al., 2009).

Moreover, the important potential of NC in providing improved efficiency in lossy networks in a distributed manner makes it an attractive option for energy constrained WBANs. The rateless nature of network codes can lower energy consumption by reducing the amount of medium access control needed, and by reducing energy used by nodes to wake up periodically to receive timing allocations from the control

base station (Shih et al., 2001). In a star network, by adapting redundancy based on transmission and reception energies for data and control packets, significant energy reduction may be achieved when NC is incorporated and as the receiving energy per control packet increases from equal to much larger than the transmitting energy per data packet (Shi et al., 2011). Achievable gains also increase as more nodes are added to the star network, and when the channels seen by different nodes become more asymmetric.

In what follows, we provide a summary of the medium access control (MAC) sublayer specifications of the 802.15.6 WBAN standard, and describe how NC can be included with minimal changes to the MAC layer, with discussions on the potential throughput and energy benefits of using a coded system.

2 THE MAC SUBLAYER SPECIFICATION OF THE IEEE 802.15.6 STANDARD

In a WBAN compatible with the IEEE 802.15.6 standard, there are multiple nodes but one and only one hub. The hub coordinates medium access among different nodes. Nodes can be arranged into a star-shaped topology, or into a two-hop extended star topology, where information are exchanged between the hub and a node via another relay-capable node.

In a WBAN, a hub may or may not provide time referenced allocations to all nodes. When it does, the MAC sublayer uses a slotted time reference model, with the time axis divided into beacon periods (superframes) of equal lengths, and each beacon period divided into allocation intervals of equal length. A frame transmission may span more than one allocation interval, with start and end times not necessarily aligned to interval boundaries. A beacon frame may be broadcasted by the hub at the beginning of or at a shifted location within each beacon period.

There are three possible access modes within a WBAN: beacon mode with beacon periods (superframes), non-beacon mode with superframes, and non-beacon mode without superframes. In beacon mode with beacon periods, a beacon frame is broadcasted at the beginning of each beacon period to specify the length of allocation intervals within the superframe, the start and stop times of the access phases present, and the number of inactive superframes to follow the current active superframe. Four types of access phases can be present in a beacon frame, covering contention-based random access, scheduled access, and improvised polling/posting.

In beacon and non-beacon modes with superframes, scheduled access may be used to obtain up-link and downlink allocations, and scheduled-polling may be used to obtain bilink allocations. To obtain one or more new scheduled allocations, a node sends a Connection Request frame to the hub, which in return sends a Connection Assignment frame to the node to grant access when possible. Existing scheduled allocations can be modified or terminated by the transmission of a new Connection Request frame.

2.1 MAC Frame Format, Frame Types and Subtypes

A MAC frame consists a header, a variable-length frame body, and a cyclic redundancy check sequence. The MAC frame body has a maximum possible length of 255 octets. The MAC header contains the sender and receiver IDs, as well as a frame control sequence.

The contents of a MAC frame differ among different frame types and subtypes. In the MAC frame header, a Frame Type field can take on four different values, representing management, data, control and reserved frames. A management type frame can be further divided into beacon, security-related, connection-related, and reserved frame subtypes. In beacon mode with beacon periods, a beacon frame is multicasted by the hub at the beginning of every beacon period. Its frame payload contains the length of the current beacon period, and timing allocation information such as the time duration of each allocation slot and start and stop times of each access interval. Data type frames are divided into subtypes depending on user priority levels and data subtypes. A control type frame is used by a node or a hub to acknowledge the recipient of a management type or a data type frame. A node or hub receiving a control type frame does not generate any further acknowledgments. In each transmitted management type or data type frame, an Ack Policy field in the MAC header indicates the type of acknowledgment requested by the current frame.

2.2 Modes of Frame Acknowledgments

The Ack Policy field of the MAC header indicates the type of acknowledgment requested. Different values represent four different policies.

No acknowledgment (N-Ack): an N-Ack indicates that the current frame does not require an acknowledgment from the recipient. A frame with an N-Ack request can be transmitted by either the hub or a node. Control type frames have their Ack Policy fields set to N-Ack.

Group acknowledgment (G-Ack): G-Acks are applicable to data frames sent to a hub. A G-Ack is requested if the frame is of data type, its Ack Policy field is set to N-Ack, and its frame subtype field is set to a pre-defined constant. The hub acknowledges frames with G-Ack requests from multiple nodes together through the use of a G-Ack multicast, in the form of a frame subtype called B2 frames. A B2 frame contains a set of node IDs (NIDs) to indicate nodes from which the hub has received a frame with G-Ack requests since the last transmitted B2 frame. A node may retry the frame with the G-Ack request if it fails to receive the expected B2 frame, or if its NID does not appear in a received B2 frame. Figure 61 of (IEEE, 2012) gives an example of G-Acks.

Immediate acknowledgment (I-Ack): a frame with an I-Ack request can be transmitted by either the hub or a node. The frame is acknowledged by an I-Ack immediately upon the frame's reception. The recipient sends back the I-Ack frame after the end of the frame reception, after a given interframe spacing, denoted by pSIFS (*e.g.* 75 μ s). Management type frames are always transmitted with an I-Ack request. Data type frames can be transmitted with a request for any one of the four acknowledgment modes.

Block acknowledgment later (L-Ack) and Block acknowledgment (B-Ack): a frame with an L-Ack or a B-Ack request can be transmitted by either the hub or a node. The transmitted frame must contain a whole MAC Service Data Unit (MSDU). Frames with L-Ack requests are not followed by any I-Acks. Instead, blocks of frames with L-Acks are acknowledged by a B-Ack frame pSISF after the reception of the last frame with a B-Ack request. Figure 63 of (IEEE, 2012) illustrates the block transmission scheme established through the use of L-Acks and B-Acks. During block transmission, the source shall send frames in the order of non-decreasing sequence numbers, with repetitions if retransmissions take place. Figure 63 of (IEEE, 2012) provides two instances of retries. All frames in a block transmission should be of the same type and subtype. A block transmission may span more than one allocation interval.

Three fields of a B-Ack frame function together to provide acknowledgments to a block of data: Oldest Frame Expected, Next Block Size, and Frame Status Bitmap. The Oldest Frame Expected field is not present if there is only one frame in the current block. When present, it is set to the sequence number of the oldest frame that is expected but has not been received. If all frames in the block has been received, the Oldest Frame Field is set to one plus the sequence number of the frame preceding the B-Ack frame. Thus, the Oldest Frame Expected field indicates the

next expected frame, assuming all frames are transmitted in order. This is similar to acknowledgments sent in the Transmission Control Protocol (TCP). The Next Block Size field is not present if only one new frame is expected and allowed. When present, it is set to the maximum number of frames that can be included in the next block transmission. The one byte-long Frame Status Bitmap field indicates the reception status of each successive frame in the block transmission, starting from the one immediately next to the oldest expected frame in sequence number. Successive frames are frames with successive sequence numbers. Hence, acknowledgments are packet specific; any un-acknowledged packet is retransmitted in the next block. Moreover, since frames in a block transmission are required to contain whole MSDUs, the recipient may implement a timeout mechanism so that MSDUs can be released to the upper layers without the reception of all frames in the block.

Other than I-Ack, B-Ack, and B2 frames, I-Ack+Poll and B-Ack+Poll control type frames can also be transmitted by the hub to grant immediate polled allocations or to announce a future poll or post request, in addition to frame acknowledgments. Moreover, a node or a hub shall treat an expected frame, such as an I-Ack or B-Ack frame, as not arriving after waiting for the physical layer preamble of the frame for a given amount of time.

3 INCORPORATION OF NETWORK CODES

A comparison between the acknowledgment modes offered by the IEEE 802.15.6 standard, and the network coding (NC) scheme in (Shi et al., 2011) shows that NC can be easily incorporated into the standard. In this subsection, we explain how this can be carried out. The quantitative advantages of network coded transmissions require detailed analysis of actual implementations of the standard. We do not attempt to characterize the performance of such systems here.

3.1 Generation-based Approach

NC can be carried out at individual nodes using a generation-based approach (Chou et al., 2003). First, the block acknowledgment mode with L-Acks/B-Acks can be used with coded frames transmitted by a node or the hub. At the transmitter side, the MAC frame payload of a given number of packets, to be transmitted in a block, can be coded together. Each block is thus a generation. With RLNC, coding coefficients can be attached as part of the payload. With de-

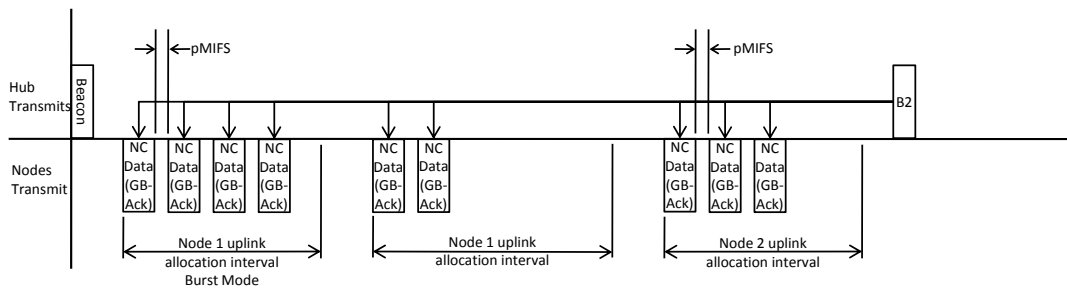


Figure 1: Example of coded data blocks with Group-Block Acknowledgments (GB-Ack).

terministic codes, coding coefficients are pre-defined. In the MAC frame control header of the transmitted frame, a reserved bit can indicate whether the current packet is coded. With coding, redundant packets can be added to compensate for potential losses. As discussed in (Shi et al., 2011), a reasonable level of redundancy can be computed heuristically. Packet loss rates can be estimated and redundancy levels can be adjusted accordingly. A systematic network code can be used to minimize coding energy. All coded frames except the last one carry an L-Ack request to the receiver, while the last coded frame carries a B-Ack request to the receiver.

At the receiver side, assuming well-chosen coefficients, each arriving packet is a unique degree of freedom (DOF), innovative to the receiver with high probability. Whenever a B-Ack request is received, the receiver can use the Frame Status Bitmap field to acknowledge to the transmitter the number of DOFs received, or the number of DOFs still expected. The Oldest Frame Expected field can be modified to indicate the generation number. When uncoded, only 9 frames can be acknowledged in each block (indicated by the Oldest Frame Expected field, plus 8 bits in the Frame Status Bitmap). With coded data, more than 9 frames can be included in a single block.

Moreover, B-Ack and G-Ack modes can be combined into a Group-Block acknowledgment (GB-Ack) mode. Figure 1 shows a possible use of GB-Acks in scheduled access mode, for data blocks uploaded from two nodes to a hub. At each node, data frames in a block are coded with random or deterministic coefficients. In the MAC frame control header of the transmitted frame, a reserved bit can be used to indicate if the current packet is coded. At the hub, a B2 frame is broadcasted at a pre-determined allocation slot when G-Acks are requested by multiple nodes. A B2 frame contains a set of NIDs, each representing a node to be group acknowledged. Since there can be a maximum of 64 nodes within a WBAN, each with a single-octet NID, but the B2 frame payload can be of 255 octets long, it is possible to append to the current B2 frame payload the numbers of DOFs successfully received

from each node for its respective current generation. For example, a one-octet field can be added to the B2 frame payload for each node from which the hub has received coded frames in the current block. The first 4 bits can represent the generation number, while the last 4 bits can represent the number of DOFs received.

There are several possible advantages of using coded transmissions with B-Acks or GB-Acks. First, independently coded packets are individual DOFs, thus acknowledgments do not need to specify which individual packet has been received successfully. In addition, with coded payloads, more than 9 frames can be included in a block transmission.

From a throughput perspective, in cases where an acknowledgment is lost and retransmission occurs without the loss of the actual data frame, a retransmitted data frame is wasteful if uncoded. By comparison, if the retransmitted frame is coded with a set of coefficients linearly independent from the previous frame, the retransmission is innovative, carrying one more DOF to the hub. In addition, in burst mode block transmissions, interframe spacing between successive frames is smaller than the I-Ack case. Thus with less frequent transmissions, the overall throughput of individual nodes can be higher. Figure 2 shows an sample timing diagram of I-Ack, B-Ack (coded or uncoded) and GB-Ack schemes. Here Guard Intervals (GT) are centrally added in between allocation intervals instead of distributively included in each allocation interval. Although we do not provide detailed computations here, it is not difficult to show that the number of data frames transmitted in an allocation interval with GB-Acks can be higher than the number of data frames transmitted in the same allocation interval with I-Acks or B-Acks, although if the allocation interval is very short, with high probability, the same number of frames fits into the interval regardless if B-Acks or GB-Acks is used. It is also not hard to see that if the number of nodes in the WBAN is large, using GB-Ack is beneficial in terms of reducing the total number of acknowledgment frames transmitted in one superframe.

From an energy perspective, given a fixed num-

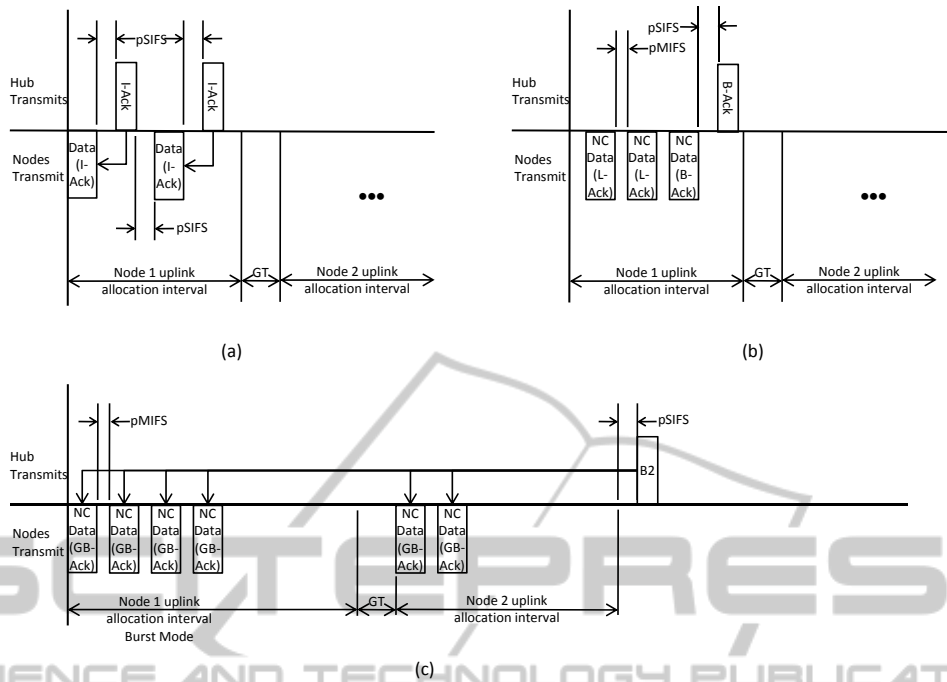


Figure 2: Timing examples (a) uncoded transmission with I-Acks; (b) coded data transmission with B-Acks and L-Acks; and (c) coded data transmission with GB-Acks.

ber of data frames to transmit by a node, block transmission requires the node to be active for a shorter period of time than when I-Acks are used. Such energy savings become more significant when switching between transmission and reception modes take up a non-negligible amount of power. Moreover, with coding, it is always possible to transmit more redundancies when listening to acknowledgment packets costs more energy. Nonetheless, coding requires additional energy, and a tradeoff exists between encoding energy and transmission/reception energy.

From a reliability perspective, coded transmissions allow redundant coded frames to be transmitted a priori to compensate for possible losses. NC thus provides another reliability mechanism, allowing less stringent requirements on PHY design. In cases where channel quality is low and scheduled allocations for a node is aborted because none of the transmitted frames is received successfully at the hub, such provision for losses may prolong the duration of the connection between a node to the hub.

3.2 Sliding Window Approach

An alternative to the generation-based NC scheme is to use a sliding window approach, as proposed by (Sundararajan et al., 2009) for interfacing NC with TCP/IP. At the transmitter, data frame payloads are put into a coding window of a fixed size as they ar-

rive from the upper layer, as long as the coding window is not full. A frame is removed from the coding window when it is acknowledged by the receiver. At the receiver, coding coefficients from received packets are put into a matrix and passed through Gaussian elimination into a reduced row echelon form. Frames on the pivot columns are taken as *seen*, and are acknowledged in the next available acknowledgment frame. In short, a receiver is said to have seen a packet \mathbf{p}_k if it can compute a linear combination of the form $\mathbf{p}_k + \sum_{l>k} \alpha_l \mathbf{p}_l$, where α_l are coding coefficients, and k represents frame sequence number. It can be shown that if all frames involved in the coding operations have been seen, all coded packets can be decoded. Seen packets are thus dropped from the coding window at the transmitter side. The notion of seen packets defines an ordering for the DOF conveyed by coded packets: for every additional DOF received at the hub, the next data frame in the coding window is acknowledged and dropped from subsequent coding operations.

The sliding window approach can be used in a WBAN similar to the generation-based approach. At the transmitter, data frame payloads are coded and sent with redundancies. At the receiver, either B-Acks or GB-Acks are used. The Oldest Expected Frame field of a B-Ack frame can be modified to represent the oldest expected seen frame. Frames which have been seen are subsequently removed from the coding

window at the transmitter. For GB-Ack frames, an Oldest Expected Seen Frame field can be added to indicate frames to be removed from the coding window of each transmitting node. A systematic code can also be used, and the transmission scheme can operate in a rateless fashion if needed.

An advantage of the sliding window approach is to allow new data to be added to the transmission queue incrementally as they arrive at the MAC sublayer and removed as soon as they are seen at the receiver. A pre-defined generation size is not required, although the size of the coding window can vary, depending on the amount of computation and memory available at sensor nodes. When data rate is not very high, fast removal of data packets from the coding window is beneficial, since fewer coding operations are performed for subsequent transmission rounds. Another advantage of the sliding window approach is that its retransmission requests are very short, since it only needs to acknowledge the last seen DOF. A disadvantage of the sliding window approach is that even though memory and energy are assumed to be abundant at the hub, decoding delay is larger. Seen packets may have to stay in the receiver queue for longer periods than the generation-based case, before they can be decoded. This problem can be mitigated if the transmitter flushes its coding window periodically.

4 CONCLUSIONS

In this article, we provide a brief description of the medium access control sublayer of the IEEE 802.15.6 WBAN standard, and consider the incorporation of network coding (NC) in WBANs compatible with the standard. Both generation-based and sliding window approaches are possible, and a group-block acknowledgment can be implemented by modifying block acknowledgment control type frames. With NC, retransmission requests are simpler, and redundant packets can be transmitted a priori, in expectation of packet losses. Such redundancies can be seen as a reliability mechanism in addition to forward error correction schemes in the physical layer. Allowing more coded packets to be sent in each round also allows the overall transmission process to terminate in fewer rounds, leading to potential savings in energy use. Since the standard only provides general rules and guidelines, actual implementations can differ in terms of hardware and signal processing algorithm design. Whether coding helps in terms of energy or throughput thus depends on how the standard is realized.

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