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Re: In response to call for technical contributions

Abstract: The performance evaluation of a hybrid ARQ scheme utilizing a decomposable error correcting code for wireless body area network based on the IEEE 802.15.6-2012 is provided. to introduce it to revision of IEEE802.15.6-2012, i.e. IEEE802.15.6ma,

Purpose: Material for discussion in P802.15.6ma TG corresponding to request from TG15.6ma committee.

Hybrid ARQ Scheme Utilizing Decomposable Error Correcting Code for Dependable WBAN

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Agenda

1. Introduction
2. Review of error control in IEEE802.15.6
3. Proposed QoS control scheme for WBAN
4. Operation of proposed scheme in multi-hop case
5. Numerical results
6. Conclusion

1. Introduction - IoMT

- **Internet of Medical Things (IoMT)**:
  - ✓ IoT in the medical and healthcare field

Fig. Triggerfish sensor (© SEED Co.,Ltd.)

- Scope of IoMT
  - ① Healthcare・Mibyo (未病)
  - ② Home Health Care
  - ③ Diagnosis
  - ④ Treatment
  - ⑤ Prognostic treatment・Rehabilitation

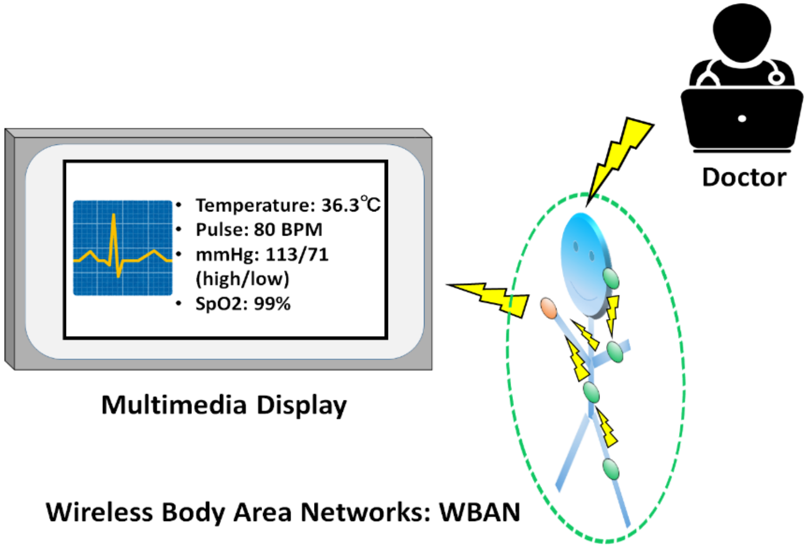
Fig. Fetal Monitor iCTG (Managed medical device (class II), © Melody International Ltd.)

- IoMT requires…
  - ✓ **Reliability** and **safety** of conventional **medical devices**
  - ✓ **Mass device management**, **reliable communication**, **heterogeneity and interoperability** of devices **more than conventional IoT**

1. Introduction

- **Wearable healthcare system** is actively studied (m-Health, tele-medicine, Internet of Medical Things (IoMT), etc.)

- As one of the IoMT system, **Wireless Body Area Networks (WBAN)** have been extensively researched



- WBAN consists of a collection of low-power, miniaturized, invasive or non-invasive lightweight sensors with wireless communication capabilities operating near the human body, and a hub controlling viral sensors

- **IEEE 802.15.6**, one of the standards of WBAN, was issued in 2012

1. Importance of QoS control

- In WBAN systems, a wearable vital sign sensor node can include **various types of sensors** with **different data rates, the allowable communication error ratio and delay**
- Therefore, **optimal QoS control for input data is an important feature** in sensor data transmission procedures

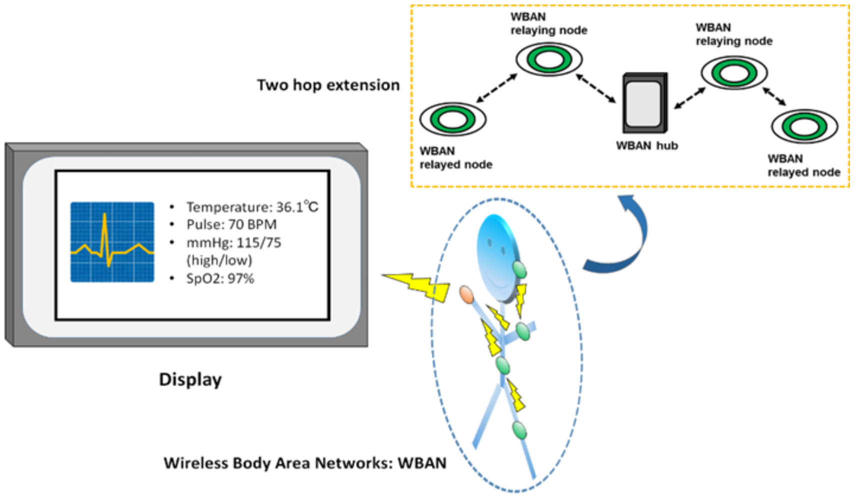
User priority	Traffic designation	Frame type
0	Background (BK)	Data
1	Best effort (BE)	Data
2	Excellent effort (EE)	Data
3	Video (VI)	Data
4	Voice (VO)	Data
5	Medical data or network control	Data or management
6	High-priority medical data or network control	Data or management
7	Emergency or medical implant event report	Data

- To address this requirement, an optimal hybrid ARQ scheme employing a **decomposable error control coding scheme** has been proposed
- The performance of the proposed system has been compared to an IEEE 802.15.6-based system, and outperformed it

1. Purpose and contribution

Purpose

- IEEE Std. 802.15.6 supports a **two-hop extension**
- In the study, the performance of a hybrid ARQ scheme for a multi-hop WBAN based on IEEE Std. 802.15.6 is evaluated under multi-path fading channel of ultra-wideband (UWB) PHY



Contribution

- **The performance of our proposed hybrid ARQ scheme (Scheme 1) is improved** by **appropriately determining the coding rate using channel estimation (Scheme 2)**
- With this improvement, data packets can be relayed to the hub **with a small number of transmissions even when the maximum number of retransmissions is limited by a two-hop extension**

2. Error control in IEEE802.15.6

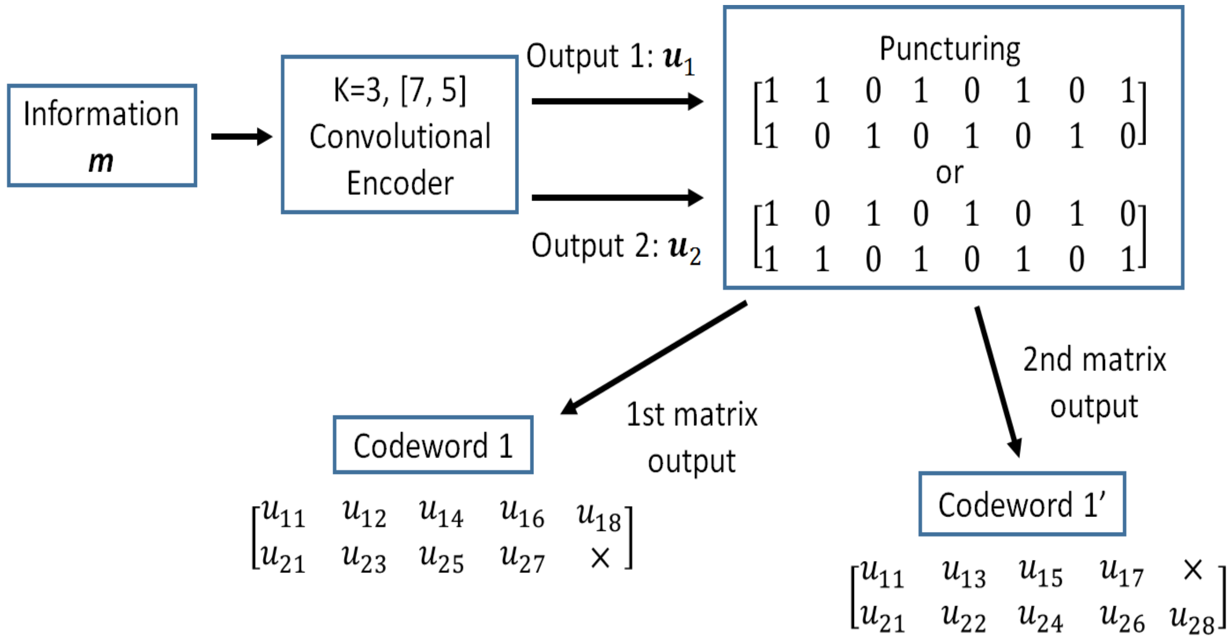
- IEEE802.15.6 shall use a (63, 51) BCH code as an error correcting code in narrowband, UWB and HBC PHY
- Only user priority 6 data in UWB-PHY may use a hybrid ARQ with a (126, 63) shortened BCH code
- WBAN may deal with 8 levels of user priority data
- Those data have a wide range of quality of service (QoS)
- The error controlling of the current IEEE Std. 802.15.6 cannot cope with it because of lack of flexibility

3. Proposed hybrid ARQ scheme for WBAN

- **Proposed QoS control scheme using decomposable error correcting codes and Weldon's ARQ protocol**

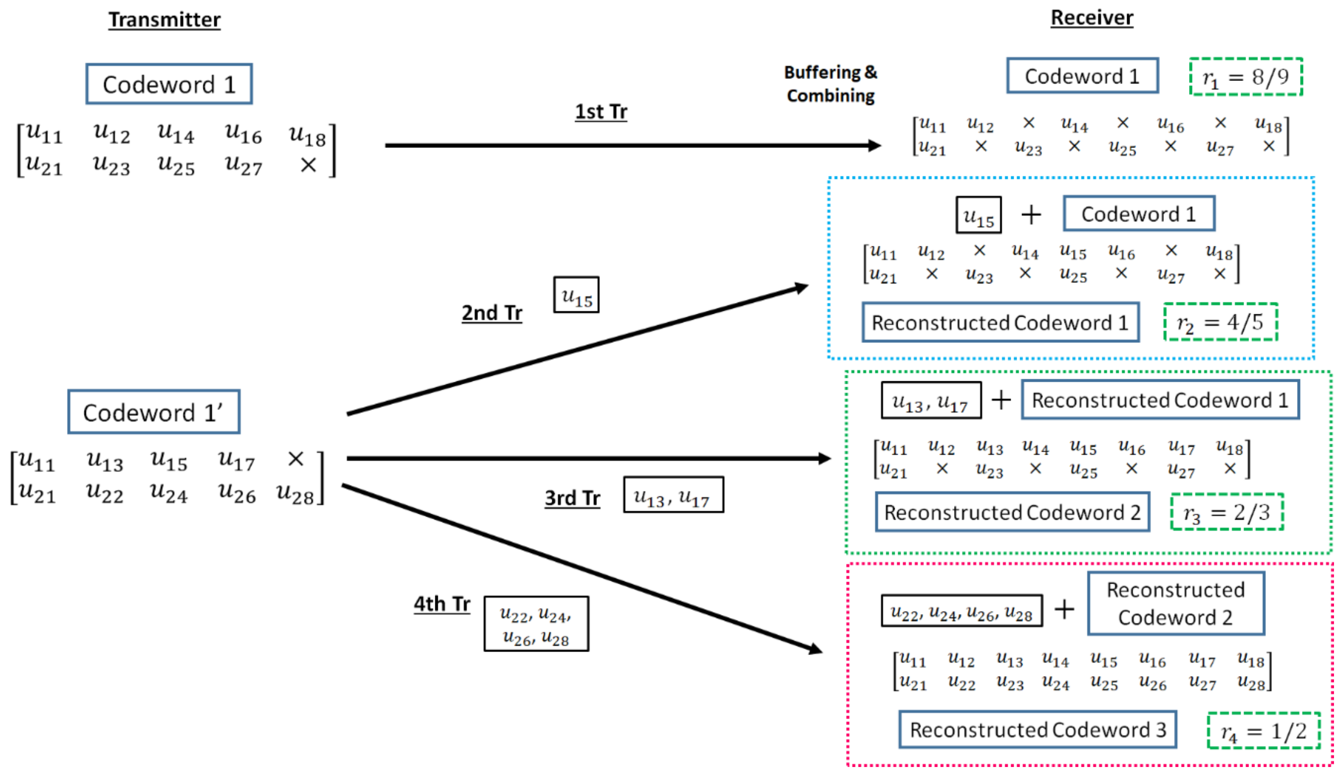
  - ✓ It is based on punctured convolutional codes (constraint length $K = 3$ and coding rates r_i of 8/9 to 1/16)
  - ✓ The $r_i = 8/9$ punctured code patterns (codeword 1 and codeword 1') are generated as shown in the next figure
  - ✓ At the first transmission, codeword 1 is sent
  - ✓ To increment the coding rate of the punctured code, elements of codeword 1' are sent after the first transmission
  - ✓ After sending all elements to reconstruct the original convolutional code, codewords 1 and 1' are transmitted alternately
  - ✓ A receiver reconstructs and decodes low-rate decomposable codes by changing the number of data copies in Weldon's ARQ protocol

3. Proposed hybrid ARQ scheme for WBAN



1. Firstly, the information bit sequence m is encoded via the punctured convolutional code, and codeword 1 is transmitted

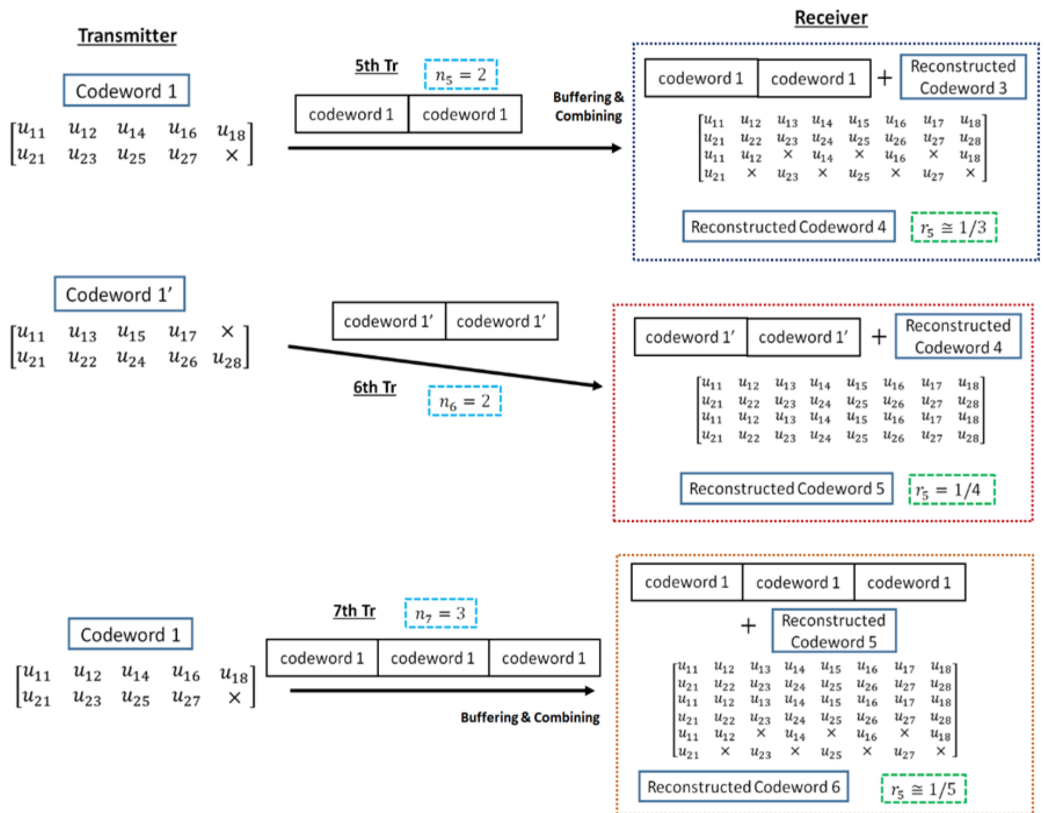
3. Proposed hybrid ARQ scheme for WBAN



2. If bit errors are detected after decoding codeword 1, the receiver stores the transmitted codeword 1, and the transmitter re-sends the sub-codeword of codeword 1' n_i times if $1 \leq i \leq 3$. At the receiver, the received sub-codeword and stored codeword are combined, and the reconstructed codeword is decoded

3. Proposed hybrid ARQ scheme for WBAN

3. After the third retransmission, codeword 1 is sent n_4 times and combined with a buffered codeword at the receiver. If bit errors are detected after decoding reconstructed codeword, the n_4 codeword 1 is buffered in the receiver, and codeword 1' is transmitted n_5 times and combined with a stored codeword



4. After that, codeword 1 and 1' are sent alternately n_i times and stored. Then, a receiver reconstructs and decodes low-rate decomposable codes by changing the number of data copies n_i in Weldon's ARQ protocol. At this time, a buffered old codeword is updated to a transmitted new codeword

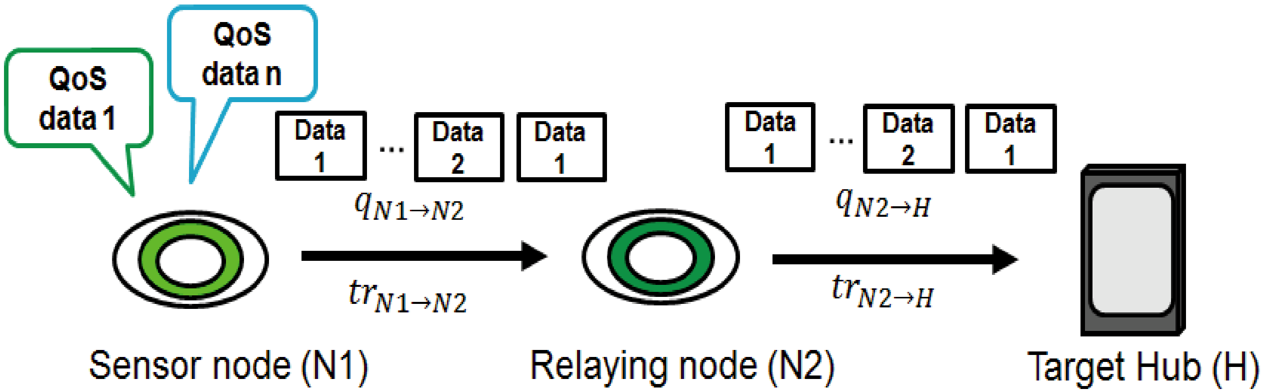
3. Proposed hybrid ARQ scheme for WBAN

- **Advantages of the proposed hybrid ARQ scheme**

1. **The coding rate is very wide**
   - Bit errors are sufficiently eliminated at the coding rate of r_c = 8/9 under very good channel conditions
   - Very low coding rates remove bit errors under bad channel conditions
   - **A coding rate at the first transmission may be changed according to channel conditions**

2. In the case of the small number of retransmissions, it is sufficient to transmit the small number of redundant bits
   - This characteristic leads to **improvement of energy efficiency and reduction of transmission delay** at retransmission

4. System model in two-hop case



- A sensor node (N1) includes multiple sensors that produce different data types that are transmitted via a relaying node (N2) to the target hub (H)
- $tr_{A \to B}$: the number of transmissions from nodes A to B, $q_{A \to B}$: the maximum number of transmissions from nodes A to B
- If bit errors are detected, the system retransmits until the maximum number of retransmissions is reached
- The transmission is considered to have failed if the data from a sensor node do not reach the target hub

4. Proposed scheme in two-hop case

- Two proposed schemes are assumed:

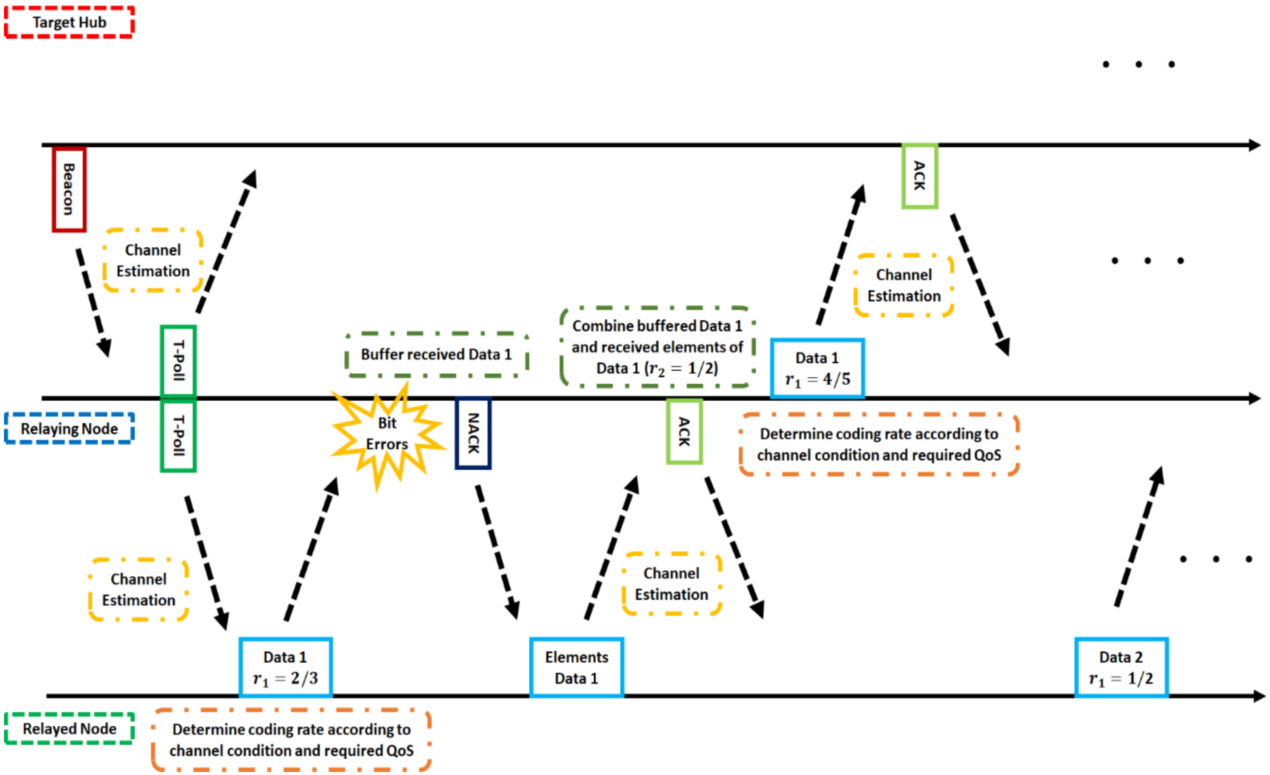
Scheme 1

- The first scheme (Scheme 1) transmits data depending on preset parameters

Scheme 2

- In the second scheme (Scheme 2), coding rates are varied with the SNR estimated using a preamble signal according to each QoS requirement
- The operation example is as follows (and a next figure):
  1. The channel SNR is estimated by using the preamble of the beacon or the T-Poll received from the hub or the relaying node
  2. The relayed node or the relaying node determines the coding rate according to the estimated channel SNR and transmits data to the relaying node or the hub
  3. If a bit error is detected, elements of the encoded data (codeword) are transmitted to increase error correcting capability after receiving NACK

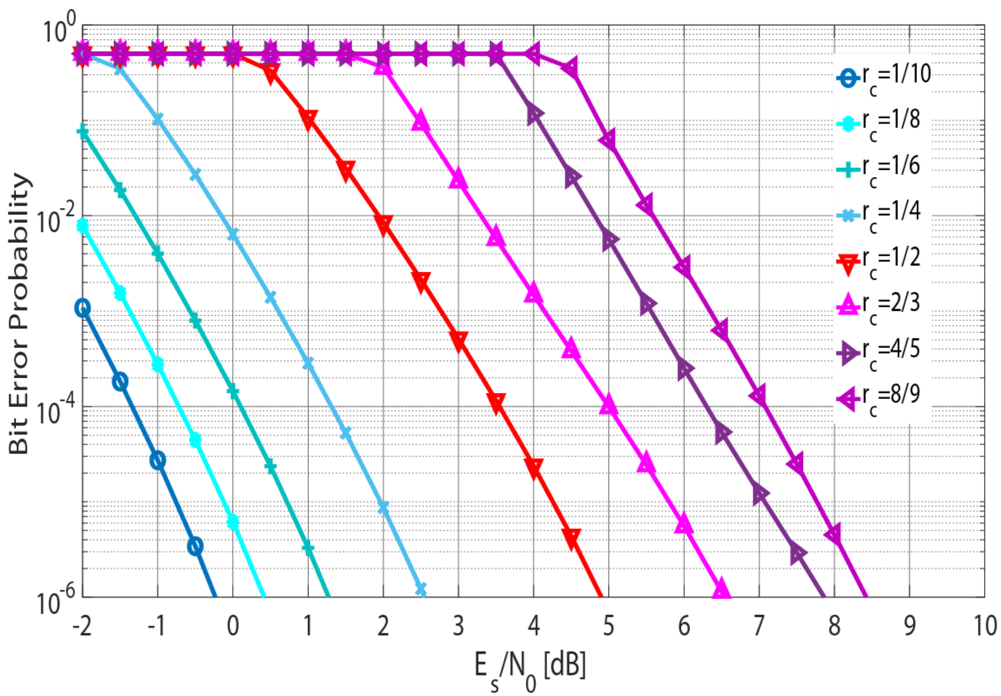
4. Proposed scheme in two-hop case



4. If data are transmitted successfully, the channel SNR is estimated by using the returned ACK preamble, the coding rate is determined, and the next data are sent

5. Since Scheme 2 uses an existing preamble, **extra overhead is not required**

4. Proposed scheme in two-hop case



- ✓ The coding rate of Scheme 2 is determined based on the desired BER and the estimated SNR from the above figure
- ✓ The desired BER is calculated from the desired PER and the length of information bit L_{info}
- ✓ For example, in case that the desired BER is calculated as 2.5×10^{-5} and the estimated SNR is 5 dB, the coding rate is determined to be $r_c = 1/2$

5. Simulation parameters

- The proposed and standard schemes with two-hop extension are evaluated based on communication distance by computer simulations
- In these computer simulations, the IEEE model CM 3 is applied as a channel model, which is targeted for wearable WBAN and includes multi-path fading
- A hospital room case in the IEEE model CM3 is utilized as a path loss model

Parameter	Detail
Channel model	IEEE model CM3
Path loss model	IEEE model CM3
Bandwidth (BW)	499.2 MHz
Central frequency (f_c)	3993.6 MHz
Pulse shape	Gaussian mono pulse
Pulse duration (T_p)	2.003 ns
Modulation	DBPSK
FEC	r_c = 8/9 to 1/16, K = 3, Convolutional codes
Decoding	Soft decision, Viterbi decoding
ARQ protocol	Weldon's ARQ
Power spectral density (P_{sd})	−41.3 dBm/MHz
Thermal noise density (N_0)	−174 dBm/Hz
Implementation losses (I)	3 dB
Receiver noise figure (NF)	5 dB
Tx RF power consumption ($P_{tx,RF}$)	37 μW
Tx circ. power consumption ($P_{tx,circ}$)	2 mW
Rx power consumption (P_{rx})	20 mW
Number of pulses per bit (N_{cpb})	2
Uncoded data rate (R)	7.8 Mbps
Synch. header duration (T_{SHR})	40.32 μs
PHY header durations (T_{PHR})	82.052 μs
Information bit length (L_{info})	306 bits
ACK length (L_{ACK})	7 bytes
Uncoded data rate (R)	7.8 Mbps

5. Each QoS of Data A and B

QoS requirements of different data types

Data types	Data A	Data B
User priority	5	6
PER	$\leq 10^{-2}$	$\leq 10^{-1}$
Energy efficiency	low	high

Maximum number of transmissions

q	$q_{N1\rightarrow N2}$	$q_{N2\rightarrow H}$	q_{max}
Data A	11	$11 - tr_{N1\rightarrow N2}$	11
Data B	5	5	10

Preset number of data copies in Weldon's ARQ n_i (Scheme 1)

i	1	2	3	4	5	6	7	8	9	10	11
Data A	1	4	4	5	5	6	6	7	7	8	8
Data B	1	1	2	3	4	-	-	-	-	-	-

- In the simulation, two data (Data A and Data B) with different types of QoS requirements are considered
- It is assumed that a low PER is desired for Data A and high energy efficiency is important for Data B
- Data A is assumed to be a physiological parameter with a low data rate, for example blood pressure, SpO2, or temperature, and Data B to be a waveform such as an ECG output

5. Compared scheme

- In computer simulations of the compared schemes, Data A was transmitted using the default mode with (63, 51) BCH code in IEEE Std. 802.15.6 and the error control scheme utilizing the (63, 55) Reed-Solomon code in IEEE Std. 802.15.4a with ordinary ARQ

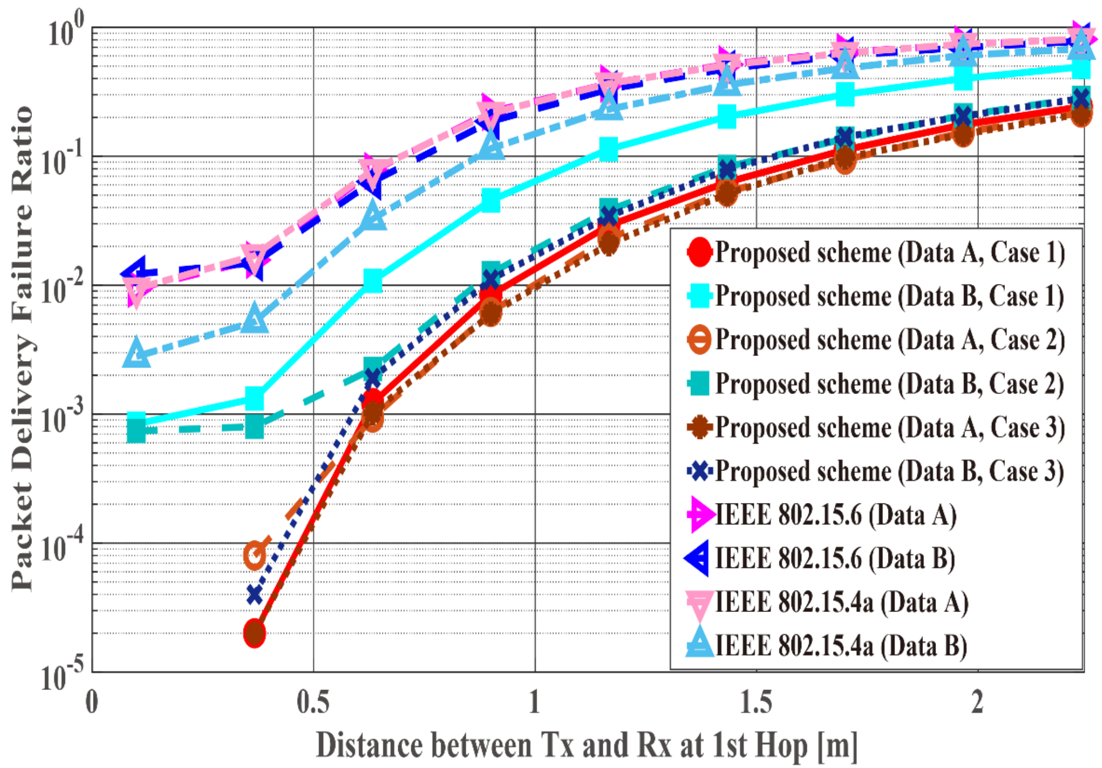
- Data B was transmitted using the high QoS mode with (126, 63) shortened BCH code and type-II hybrid ARQ, and then the error control scheme utilizing the concatenated code consisting of the (63, 55) Reed-Solomon code and the convolutional code whose constraint length is three and coding rate is 1/2 in IEEE Std. 802.15.4a with ordinary ARQ

- Each case of the proposed scheme in each hop is summarized as shown in the next table

Cases for the proposed scheme of each hop

	$N1 \rightarrow N2$	$N2 \rightarrow H$
Case 1	Scheme 1	Scheme 1
Case 2	Scheme 1	Scheme 2
Case 3	Scheme 2	Scheme 2

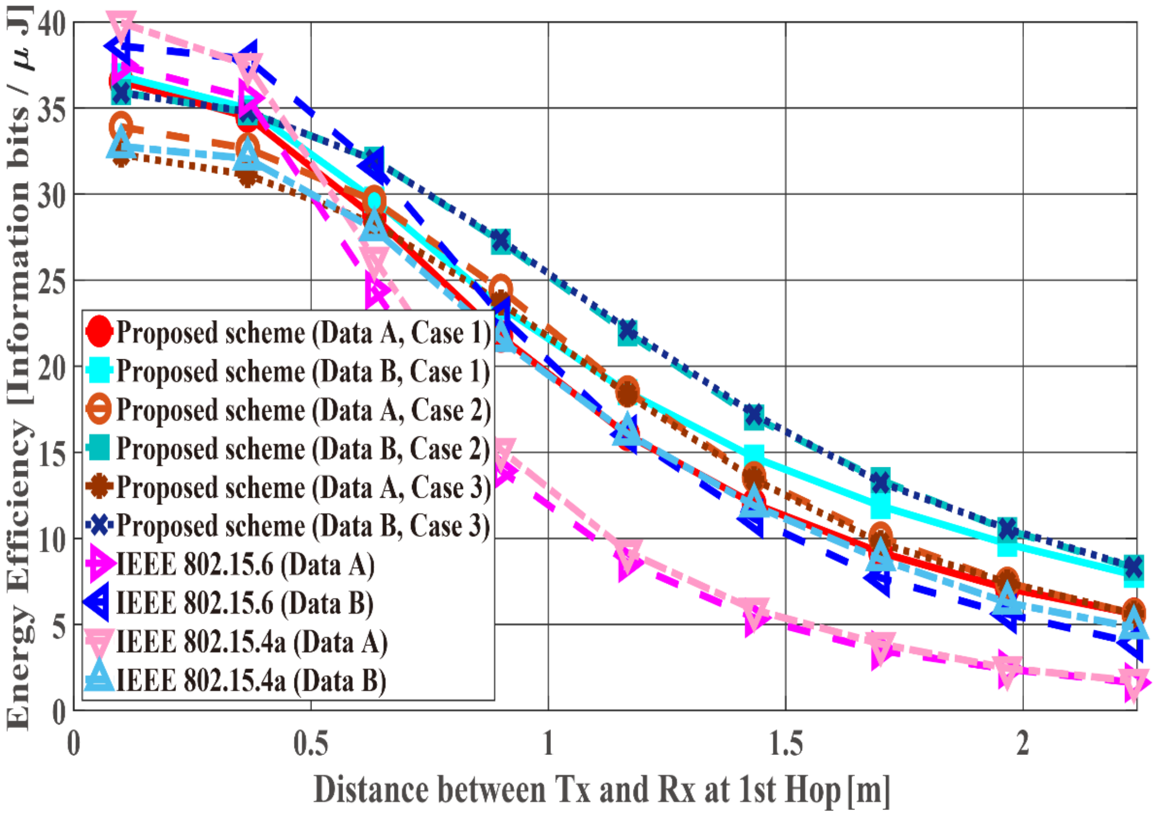
5. Numerical results



Packet delivery failure ratio with constant $d_{2nd} = 40$ cm, the distance of the first hop d_{1st} is changed from 10 centimeters (cm) to 2.2 m

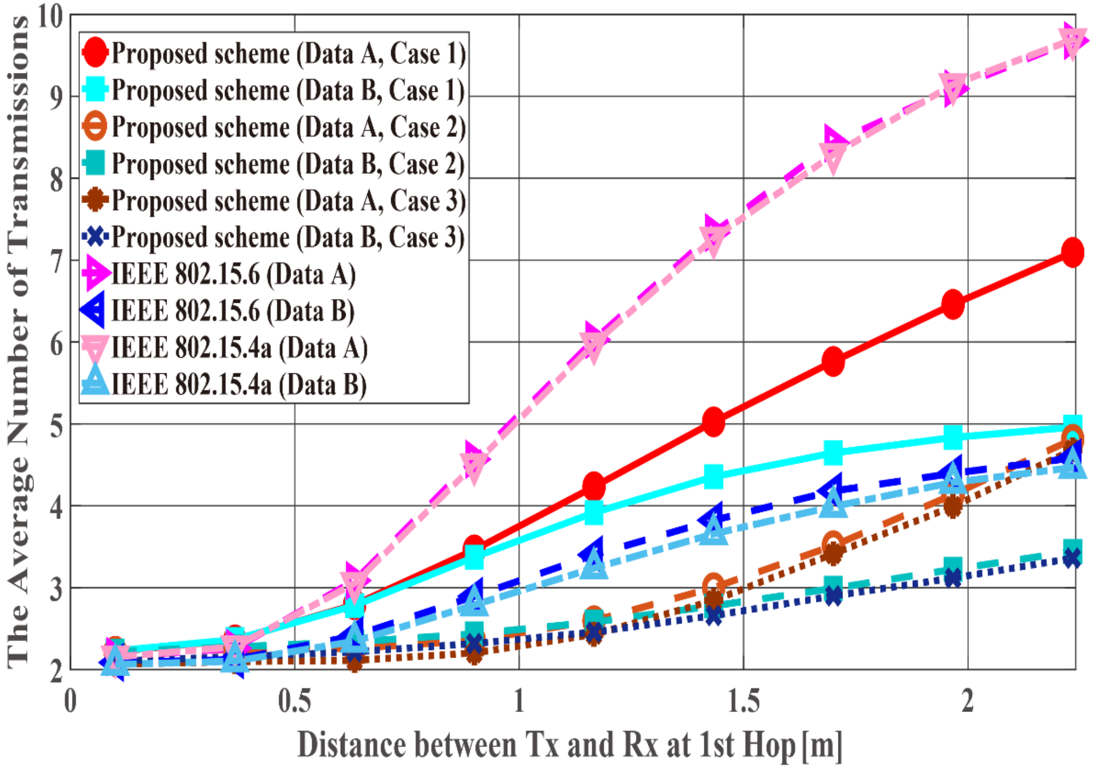
- ✓ PDFR means the ratio at which the two-hop relay failed beyond the maximum number of retransmissions

5. Numerical results



Energy efficiency with constant $d_{2nd} = 40$ cm, the distance of the first hop d_{1st} is changed from 10 centimeters (cm) to 2.2 m

5. Numerical results



Average number of transmissions with constant $d_{2nd} = 40$ cm, the distance of the first hop d_{1st} is changed from 10 centimeters (cm) to 2.2 m

5. Consideration (constant d_{2nd} case)

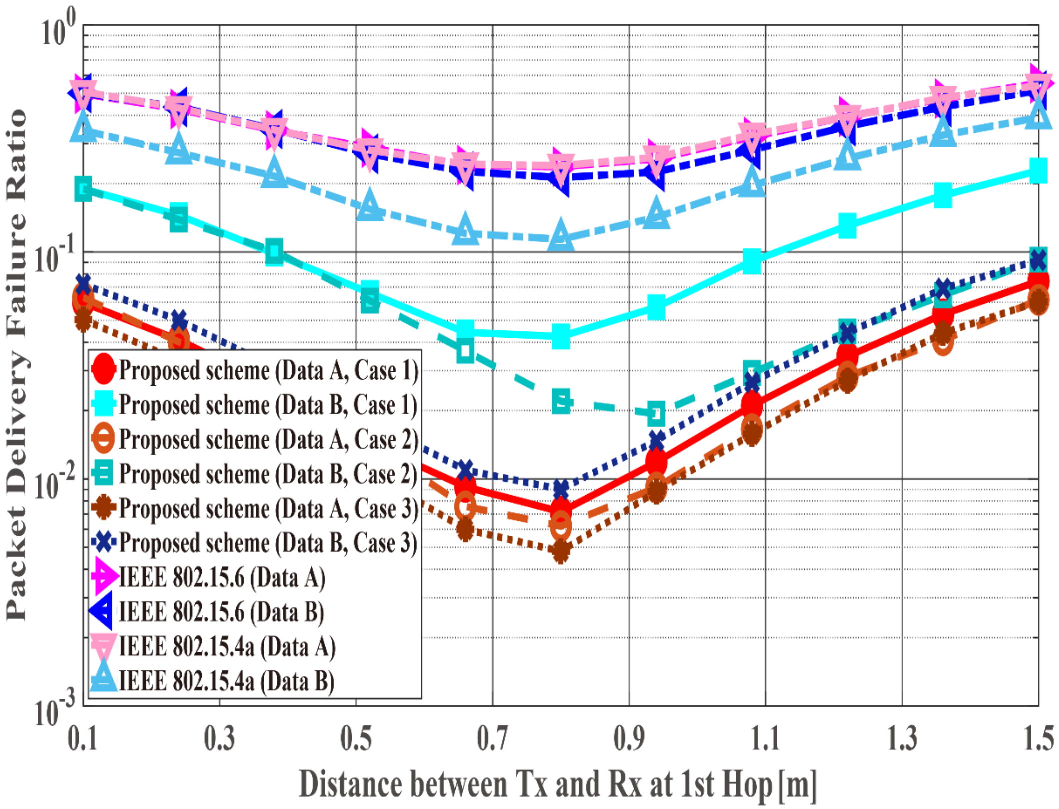
- **The proposed scheme satisfies the QoS requirements for data A** and, while **IEEE Std. 802.15.6 and 15.4a do not**

- Data B has better performances with respect to both standard schemes
  - **Those standard schemes are not basically designed so that any QoSs can be satisfied**
  - That is one of problems in those standard schemes

- Cases 2 and 3 show better energy efficiency and average number of transmissions than Case 1
  - **The coding rate of Case 2 and Case 3 is set appropriately for the channel SNR** and the number of retransmissions is reduced by utilizing Scheme 2
  - Case 1 uses only Scheme 1 and it requires a larger number of retransmissions

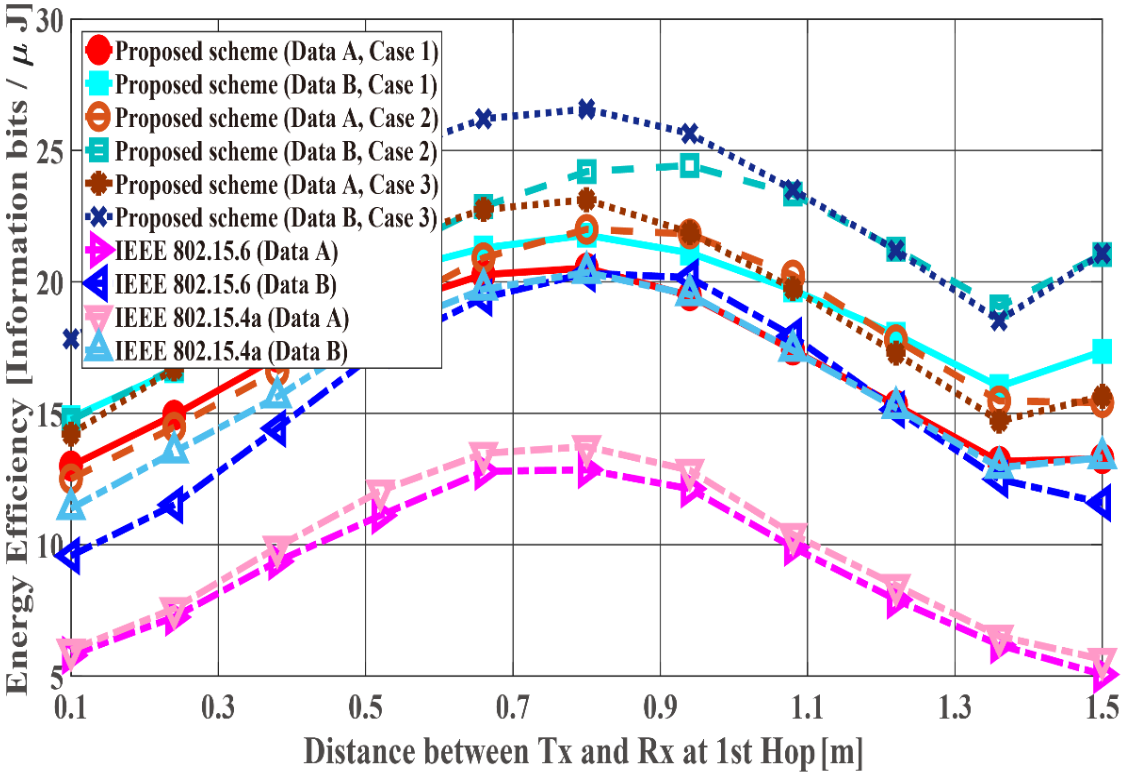
- There is not a large difference between Cases 2 and 3
  - **d_{2nd} is short and the error correcting capability** of coding rate r_c = 8/9 **at the first transmission can reduce bit errors sufficiently**

5. Numerical results



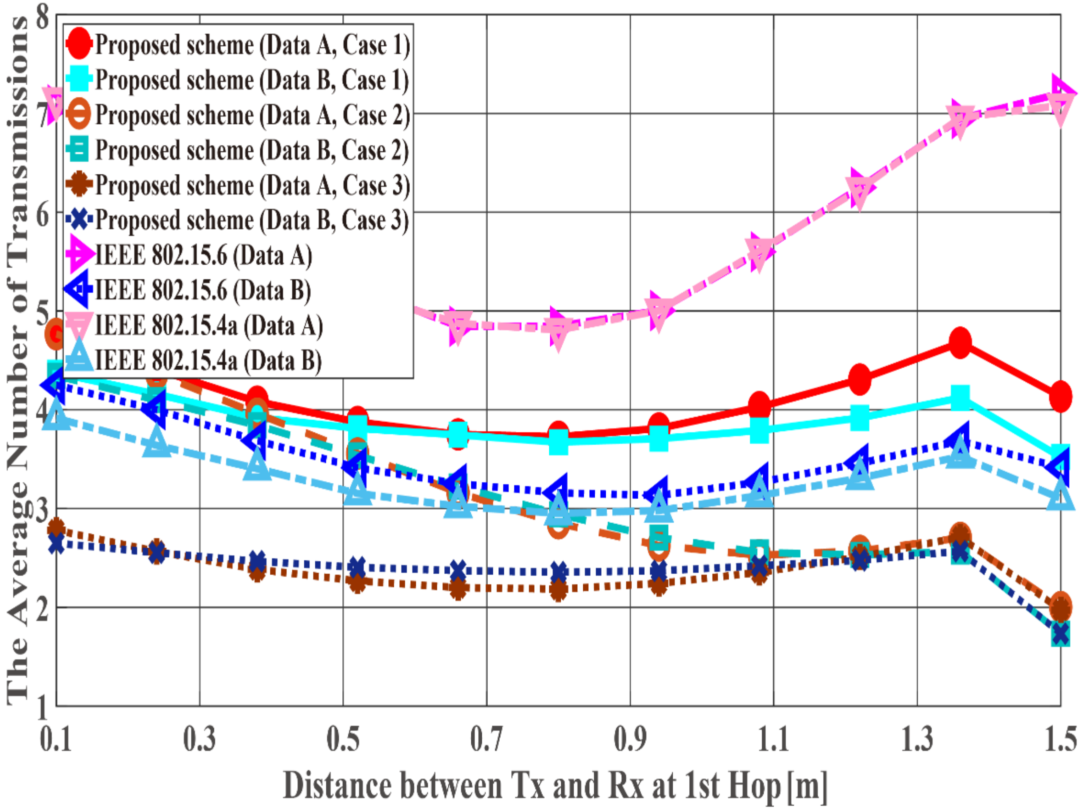
Packet delivery failure ratio with constant $d_{2hops} = d_{1st} + d_{2nd} = 1.5$ m varying the d_{1st} and d_{2nd} values. For $d_{1st} = 1.5$ m, data are transmitted using only a single hop.

5. Numerical results



Energy efficiency with constant $d_{2hops} = d_{1st} + d_{2nd}$ = 1.5 m varying the d_{1st} and d_{2nd} values. For d_{1st} = 1.5 m, data are transmitted using only a single hop.

5. Numerical results



Average number of transmissions with constant $d_{2hops} = d_{1st} + d_{2nd}$ = 1.5 m varying the d_{1st} and d_{2nd} values. For d_{1st} = 1.5 m, data are transmitted using only a single hop.

5. Consideration (constant d_{2hops} case)

- **The proposed scheme satisfies the QoS requirements for Data A and B**, while **both standard schemes approach do not** like the first scenario

- **The performances of both standards are worse than the proposed one**
  - For example, Data A of the proposed scheme satisfies PDFR $<10^{-2}$, while that of both standards do not satisfy PDFR $<10^{-1}$
  - The correcting capability of error correcting codes used in those standards is lower than that of the proposed scheme

- Comparing Case 1 and Case 2, Case 2 has better characteristics
  - **Case 2 can select a coding rate suitable for the channel condition by using Scheme 2 at the second hop**
  - Regarding Case 1, since Scheme 1 is used at both hops, it is considered that a hop having a bad channel condition is greatly affected

- **Case 3 shows the best performance because Scheme 2 is used at both hops**
- **All cases (except Case 2) achieve optimal performance when $d_{1st} = d_{2nd} = \frac{d_{2hop}}{2}$**

6. Conclusion

- The performance of our proposed hybrid ARQ scheme **in the case of two-hop extension** was evaluated
- The PDFR, number of transmissions, and energy efficiency of our proposed system, IEEE Std. 802.15.6 and 15.4a were evaluated for this case
- The numerical results show that **the proposed scheme outperforms those standard schemes**
- **Case 3 (i.e., the coding rates change depending on the channel's condition) showed better performance than the other cases at both hops**
- When d_{2hops} was fixed, it was shown that **performance became optimal when $\boldsymbol{d_{1st} = d_{2nd}}$ (except Case 2)** from computer simulations
- This result is expected to greatly contribute to the optimization of how nodes and hubs are arranged when designing a WBAN

Reference

- Kento Takabayashi, Hirokazu Tanaka, Chika Sugimoto, Ryuji Kohno, "Performance Evaluation of Error Control Scheme in Multihop WBAN Based on IEEE802.15.6," The International Symposium on Information Theory and Its Applications 2016 (ISITA 2016), Monterey, California, US, pp.370-374, Oct. 2016.

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- Kento Takabayashi, Hirokazu Tanaka, Chika Sugimoto, Katsumi Sakakibara, Ryuji Kohno, "Cross-layer Design and Performance Analysis of Quality of Service Control Scheme for Wireless Body Area Networks," IEEE Access, vol.5, pp.22462-22470, Nov. 2017.

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Apendix

1. Introduction - UWB

- IEEE 802.15.6 defines three physical layers
  - ✓ Narrowband
  - ✓ **Ultra-wideband (UWB)**
  - ✓ Human body communication (HBC)

- **UWB technology has recently regained attention (introduction to iPhone and AirTag, support for Android 12)**

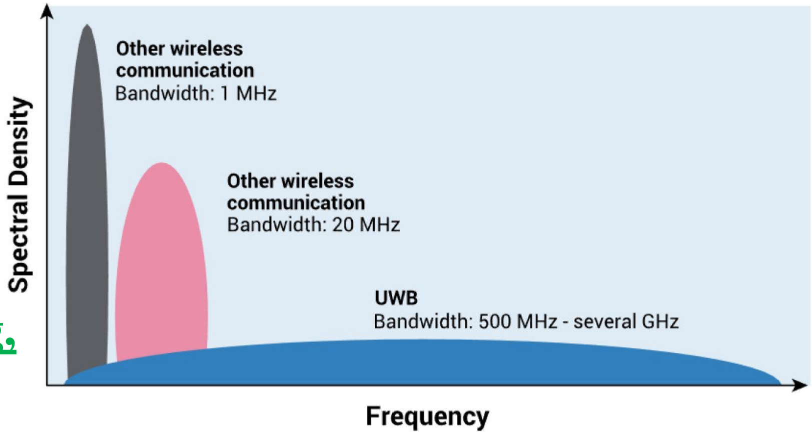


Fig. UWB Frequency Spectol

- UWB offers…
  - ✓ high data rate transmission
  - ✓ **Ultra-high-precision positioning**
  - ✓ low energy consumption
  - ✓ powerful multi-pass resolution
  - ✓ good coexistence with other wireless communication systems

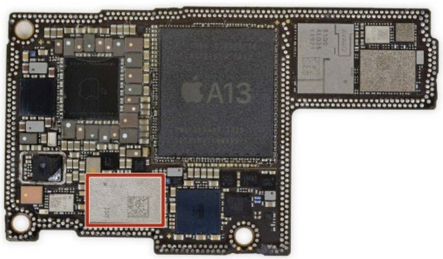
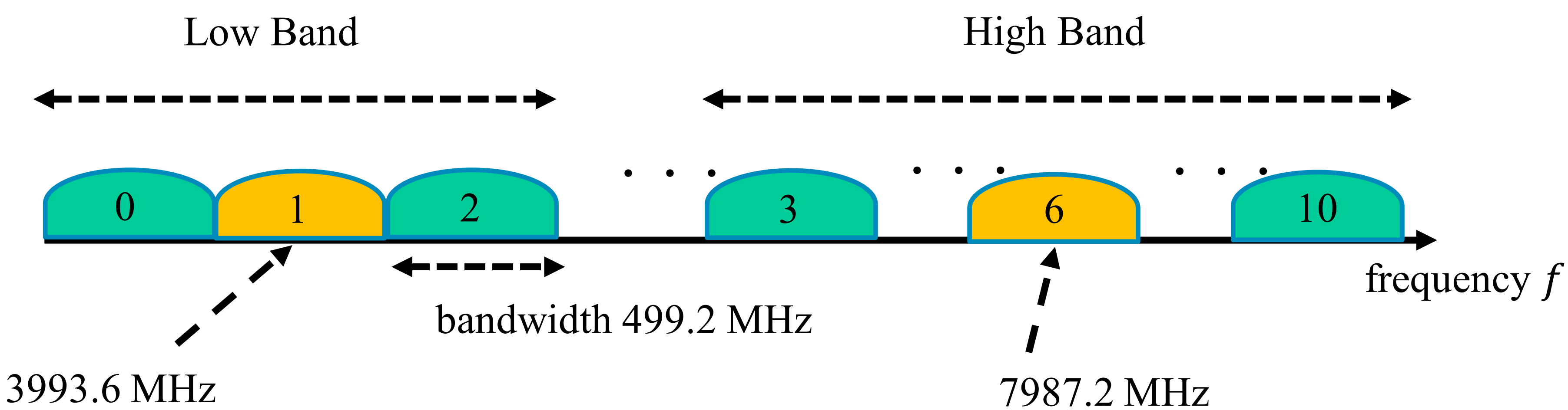


Fig. U1 in iPhone 11

- UWB is a technology that may satisfy the requirements of IoMT

2. IEEE 802.15.6 UWB PHY

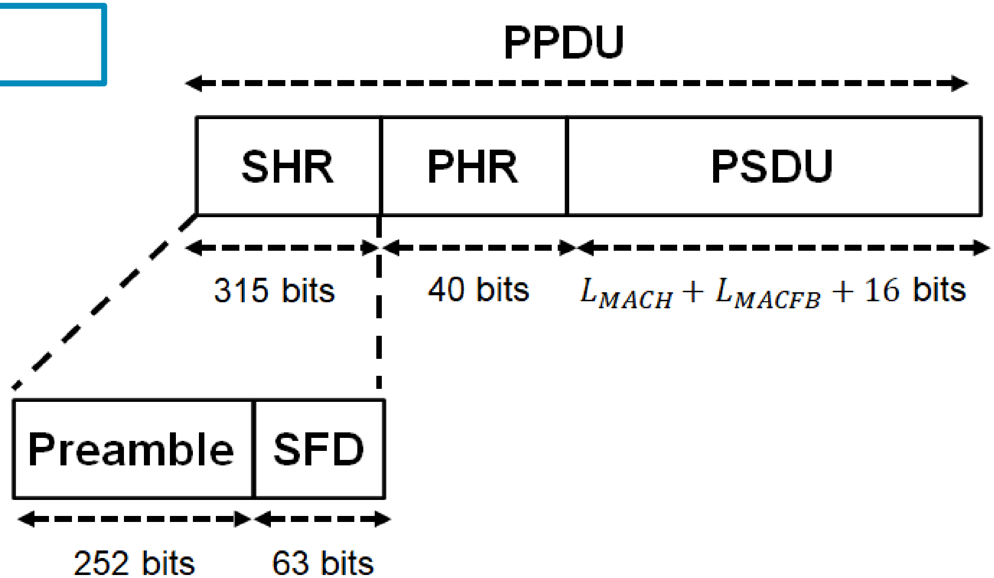
Frequency spectrum



- The UWB band is divided into two band groups: low band (channel 0-2) and high band (channel 3-10) which are divided into operating frequency channels with 499.2 MHz bandwidth
- Orange colors are mandatory channels (Low Band: channel 1， High Band: channel 6)
- The power spectral density emission limit is **-41.3 dBm/MHz which is very low**

2. IEEE 802.15.6 UWB PHY

Frame format



- SHR is divided into two parts: The first part is the preamble, intended for timing synchronization, packet detection, and carrier frequency offset recovery, and The second part is the start-of-frame delimiter (SFD) for frame synchronization
- The PHR contains information about the data rate of the PSDU, length of the medium access control (MAC) frame body, pulse shape, burst mode, and so on
- The PSDU contains the MAC protocol data unit (MPDU)

2. IEEE 802.15.6 UWB PHY

Modulation

- In the IR-UWB PHY, the bits of the physical layer protocol data unit (PPDU) are modulated by either on–off modulation or differentially encoded binary phase shift keying (DBPSK)/quadrature phase shift keying (DQPSK)
- This research assumes DBPSK

Error detection and correction codes

- PHR: CRC-4 ITU is applied as the error detection code, and (40, 28) shortened BCH code is applied as the error correction code
- PSDU: CRC-16-CCITT is applied as the error detection code, and (63, 51) BCH code or (126, 63) shortened BCH code is applied as the error correction code
- In this study, (63, 51) BCH code is applied as the error correction code of PSDU ((126, 63) shortened BCH code is used in combination with Type II Hybrid ARQ)

2. IEEE 802.15.6 UWB PHY

Pulse option

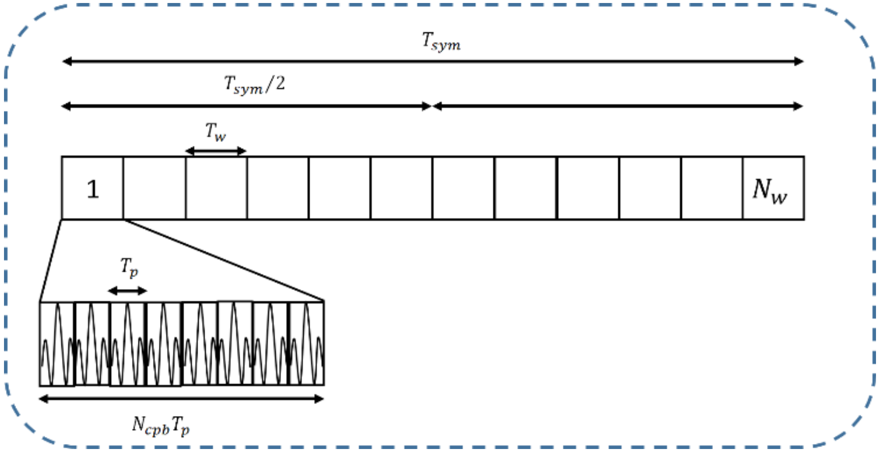


Fig. Signal transmission example where the burst pulse option is used

Transmitting signal

$$x(t) = \sum_{m=0}^{N} c_m w\left(t - mT_{sys} - h^{(m)}T_w\right)$$

$$w(t) = \begin{cases} p(t) \\ (\text{Single Pulse Option}, T_w = T_p) \\ \sum_{i=0}^{N_{cpb}-1} (1 - 2s_i)p\left(t - iT_p\right) \\ (\text{Burst Pulse Option}, T_w = N_{cpb}T_p) \end{cases}$$

- Single pulse option: A single pulse transmitted per symbol
- Burst pulse option: A concatenation of N_{cpb} pulses transmitted per symbol
  - ✓ This option reduces the data rate while improving the received power by correlating multiple pulses

2. IEEE 802.15.6 UWB PHY

Table 68—Data rates for DBPSK/DQPSK modulations

R_0,R_1, R_2	PRF (MHz)	N_w	N_{hop}	T_w (ns)	S_f	T_{sym} (ns)	Mod	Uncoded bit rate (Mbps)	FEC rate	Coded bit rate (Mbps)	N_{cpb}	P.PRF (MHz)
0 0 0	0.487	32	32	64.103	1	2051.300	DBPSK	0.487	0.5	0.243	32	499.2
1 0 0	0.975	32	32	32.051	1	1025.600	DBPSK	0.975	0.5	0.457	16	499.2
0 1 0	1.950	32	32	16.026	1	512.820	DBPSK	1.950	0.5	0.975	8	499.2
1 1 0	3.900	32	32	8.012	1	256.410	DBPSK	3.900	0.5	1.950	4	499.2
0 0 1	7.800	32	32	4.006	1	128.210	DBPSK	7.800	0.5	3.900	2	499.2
1 0 1	7.800	32	32	4.006	1	128.210	DQPSK	15.600	0.5	7.800	2	499.2
0 1 1	3.906	32	32	8.012	7	1794.900	DBPSK	0.557	0.5	0.278	4	499.2
1 1 1	3.906	32	32	8.012	7	1794.900	DQPSK	1.114	0.5	0.557	4	499.2

S_f = spreading factor, Mod = modulation, ns = nanoseconds.

- N_{cpb} is the power of two
- As N_{cpb} increases, a data rate decreases
- Data rate and received signal to noise ratio (SNR) are in a trade-off relationship