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ENABLING IPV6 OVER CROSS-TECHNOLOGY COMMUNICATION WITH WAKE-UP RADIO FOR ENHANCED CONNECTIVITY

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ABSTRACT

This paper addresses the interoperability challenges among IoT devices using different wireless technologies, such as IEEE 802.15.4 and IEEE 802.11. It introduces a bidirectional Cross-Technology Communication with Wake-up Radio (WuR-CTC) approach to enable connectivity without a gateway. The key innovation is the design, implementation, and evaluation of an adaptation layer that supports IPv6 over WuR-CTC, utilizing the IETF Static Context Header Compression and fragmentation (SCHC) framework. Experimental results demonstrate successful transmission of a 127-byte IPv6 packet from an IEEE 802.15.4 device to an IEEE 802.11 device in 69 ms on average, without the need for a gateway. This solution is particularly beneficial for latency-sensitive applications in smart environments requiring real-time device interaction.

Index Terms *Internet of Things, Cross-Technology Communication, Wake-up radio, SCHC, IPv6, Compression, Fragmentation, LPWAN.*

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1. INTRODUCTION

The paper tackles a critical challenge in the Internet of Things (IoT) landscape—establishing direct communication between IoT devices using IEEE 802.11 and IEEE 802.15.4 wireless technologies, eliminating the need for an intermediary gateway. Interoperability is a key consideration in IoT scenarios, and this becomes particularly crucial in smart home applications where both IEEE 802.11 and IEEE 802.15.4 are commonly utilized.

The research introduces a promising solution to this challenge in the form of a Cross-Technology Communication (CTC) method named WuR-CTC. This approach leverages Wake-up Radio (WuR) channels to facilitate bidirectional communication between devices operating on the IEEE 802.11 and IEEE 802.15.4 wireless technologies. WuR-CTC offers the potential for seamless interaction among diverse IoT devices, contributing to the realization of more efficient and integrated smart home environments.

While highlighting the advantages of WuR-CTC, the paper acknowledges a limitation—specifically, the lack of support for IPv6, a fundamental protocol for Internet communication. IPv6 support is essential for achieving full protocol stack interoperability and ensuring that devices can communicate effectively in a standardized manner. To address this limitation, the authors present an innovative adaptation layer that makes use of the IETF Static Context Header Compression and fragmentation (SCHC) framework. This adaptation layer serves as a bridge, enabling the transmission of IPv6 over WuR-CTC and ensuring that devices can communicate seamlessly despite differences in their underlying wireless technologies.

The adaptation layer's integration with the SCHC framework is a noteworthy aspect of the solution. SCHC is a compression and fragmentation framework designed for IoT environments where devices may have limited resources. By incorporating SCHC, the authors enhance the efficiency of IPv6 packet transmission over WuR-CTC. This adaptation layer becomes a crucial component in achieving not only interoperability between IEEE 802.11 and 802.15.4 devices but also compatibility with a standard Internet communication protocol.

The comprehensive evaluation conducted by the authors adds a robust layer of validation to their proposed solution. The evaluation considers various key factors, including IPv6 packet compression ratio, error rate, frame count, overhead, transfer time, and throughput. The results of the evaluation are promising, indicating the successful transfer of IPv6 packets over WuR-CTC. Moreover, the solution demonstrates its efficacy in supporting real-time interactions between devices without the need for an intermediary gateway.

The research findings underscore the practical applicability of the proposed solution in smart home environments, where low-latency communication is crucial for the seamless functioning of interconnected devices. The ability of the solution to handle different packet sizes efficiently further enhances its versatility and suitability for various IoT scenarios.

2. RELATED WORK

The paper delves into the realm of Cross-Technology Communication (CTC) within IoT scenarios, specifically addressing the interoperability challenges between IEEE 802.11 and IEEE 802.15.4 devices. The necessity of achieving bidirectional communication without the reliance on a gateway is a critical concern in the context of seamless and efficient IoT operations, particularly in smart home applications.

The introduction provides an insightful review of various CTC methods, emphasizing bidirectional communication. Notable methods like WEBee, LongBee, FreeBee, and WiZig are compared, each presenting unique advantages and limitations. The paper identifies a gap in the existing literature—

none of the reviewed works provide IPv6 support over CTC, setting the stage for the authors to propose a novel solution in the form of WuR-CTC.

WuR-CTC leverages the innovative concept of Wake-up Radio (WuR) channels to enable direct communication between devices operating on different wireless technologies. However, the absence of IPv6 support prompts the authors to introduce a crucial component—an adaptation layer built on the IETF Static Context Header Compression and fragmentation (SCHC) framework. This adaptation layer serves as a bridge, ensuring that IPv6 can be effectively transmitted over WuR-CTC, thereby addressing the identified gap in the literature.

The paper takes a deep dive into the features and benefits of SCHC, showcasing its superiority over other header compression techniques such as ROHC and 6LoWPAN. The evaluation results underscore SCHC's smaller header size, lower overhead, and improved performance, particularly in Low Power Wide Area Network (LPWAN) scenarios. This positions SCHC as a robust candidate for the adaptation layer, providing a solid foundation for enabling IPv6 support over WuR-CTC.

The versatility of SCHC is a key focus in the paper, extending its application beyond the immediate context of supporting IPv6 over CTC. The exploration of SCHC in mobility scenarios, multimodal communication, and LPWAN deployments showcases its adaptability to various IoT scenarios. The paper provides a comprehensive assessment of SCHC's performance in terms of reliability, goodput, energy consumption, and network capacity, reinforcing its suitability for diverse applications.

While SCHC has been extensively studied in the context of LPWAN technologies, the paper brings attention to a significant gap in the literature—its application to support IPv6 over CTC technologies. The proposed adaptation layer utilizing SCHC emerges as an innovative solution, filling this void and contributing to the advancement of CTC methodologies. The paper concludes by summarizing the key contributions, emphasizing the unique aspects of the proposed adaptation layer, and highlighting potential applications in the broader landscape of IoT and smart home technologies.

3. Cross technology communication with WuR

The paper highlights the WuR-CTC (Wake-up Radio Cross-Technology Communication) as a distinctive Cross-Technology Communication (CTC) method, facilitating communication between IEEE 802.15.4 and IEEE 802.11 devices without a gateway. The system involves a Wake-up Receiver (WuRx) waiting for a Wake-up Signal (WuS) sent by the main radio of another device (WuTx), enabling bidirectional communication. The WuR-CTC system consists of a Physical Layer and a Link Layer.

3.1. WuR-CTC Physical Layer Overview:

- Transmission Rate and Modulation:

- WuR-CTC utilizes a single transmission rate of 250 kbps employing On-Off Keying (OOK) symbols. This ensures a balance between data rate and power efficiency.

- Physical Protocol Data Unit (PPDU):

- Defines a structured PPDU that includes essential components such as a preamble sequence, frame delimiter, and Physical Service Data Unit (PSDU). This delineation ensures standardized communication between devices.

- Encapsulation Formats:

- WuRx decodes the PPDU using two encapsulation formats. For compatibility with IEEE 802.11 WuTx, the PPDU is encapsulated in an IEEE 802.11g frame. In contrast, for compatibility with IEEE 802.15.4 WuTx, an ideal square OOK symbol is generated.

3.2. WuR-CTC Link Layer Overview:

- Sublayers:

- The Link Layer comprises two primary sublayers: the Medium Access Control (MAC) sublayer and the Logical Link Control (LLC) sublayer.

- MAC Sublayer:

- Utilizes 10-bit unicast addresses and employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for both IEEE 802.11 WuTx and IEEE 802.15.4 WuTx. This approach minimizes interference during data transmission.

- LLC Sublayer:

- Includes crucial components such as ACK frames, sender transmission timer, and receiver transmission timer, specifically designed for efficient communication and energy-saving sleep mode operation.

- WuR-CTC MPDU:

- Defines the MAC Protocol Data Unit (MPDU) with essential fields like receiver and sender addresses, type field, sequence number, length field, MPSU (MAC Payload Service Unit), and CRC (Cyclic Redundancy Check). This standardized format ensures consistency in data exchange.

3.2.1. WuR-CTC Frame Types:

- Diverse Frame Types:

- The frame type field encompasses Data, ACK, and WuS flags, leading to the definition of five distinct frame types. These include WAKE, ACK, DATA, WAKE+DATA, and ACK+DATA, with provisions for two additional reserved types for future expansion.

- ACK Handling:

- Notably, the ACK frame type does not receive a reply with another ACK, streamlining the communication process and optimizing resources.

3.3. WuR-CTC Message Exchange Overview:

- Message Exchange Process:

- Describes the comprehensive message exchange process within WuR-CTC, involving a series of well-defined frame exchanges between the sender and receiver.

- Communication Initiation:

- The process starts with the initiation of communication using a WAKE frame, followed by ACK frames, DATA frames in a stop-and-wait pattern, and concludes with a SLEEP frame. This organized structure ensures effective data transfer.

- Energy Efficiency:

- Illustrates the message exchange process through a 3-way handshake, data transfer utilizing ACK frames, and a concluding sleep frame. This design emphasizes energy efficiency, a critical consideration in IoT and smart home environments.

By detailing each aspect of WuR-CTC's Physical and Link Layer, as well as the frame types and message exchange process, the paper provides a thorough understanding of the protocol's structure, functionality, and efficiency in facilitating direct communication between IEEE 802.15.4 and IEEE 802.11 devices in smart home scenarios.

4. STATIC CONTEXT HEADER COMPRESSION AND FRAGMENTATION OVERVIEW

This section provides an overview of the SCHC (Static Context Header Compression) framework, organized into three subsections: SCHC adaptation layer, SCHC header compression (C/D), and SCHC fragmentation and reassembly (F/R).

4.1. SCHC Adaptation Layer:

- Modeling as an Adaptation Layer: SCHC serves as an adaptation layer situated between the upper layer (e.g., network layer) and the data link layer.
- Sublayers: SCHC comprises two sublayers: Compression/Decompression (C/D) and Fragmentation/Reassembly (F/R).
- Profiles: SCHC is designed as a generic specification with the flexibility for parameter values and operational modes. Specific additional documents, called Profiles, are required for using SCHC over particular technologies.

4.2. SCHC Header Compression (C/D):

- Operation: When a sender intends to transmit a packet, SCHC operates in two steps: C/D and F/R.
- Header Compression: The C/D sublayer performs header compression by utilizing a static context shared between sender and receiver.
- Static Context: The static context is based on predictability in IoT traffic, allowing the compression of header field values known a priori.
- RuleID: Rules in the static context are identified by RuleID, each containing partial or full values of packet header fields.
- Compression Output: The output of the compression process is a SCHC Packet with a header containing RuleID and compression residue.

4.3. SCHC Fragmentation and Reassembly (F/R):

- F/R Modes: SCHC provides various F/R modes designed to support different requirements and networking environments, e.g., in terms of link bidirectionality and reliability.
- ACK-Always Mode: Designed for in-sequence fragment delivery with SCHC ACK messages sent regardless of fragment delivery errors.
- Fragmentation Process: SCHC Packet is fragmented into tiles, grouped into windows. The SCHC Fragment contains fields like RuleID, DTag, Window Number (W), FCN, and Reassembly Check Sequence (RCS).
- SCHC ACK Format: Sent by the receiver at the end of a window to report whether the tiles have been received or not. It includes RuleID, DTag, W, FCN, integrity check bit (C), and a bitmap.
- Timers: SCHC ACK-Always mode provides Retransmission and Inactivity timers for reliable communication.

5. SCHC over wur-CTC profile design

5.1 SCHC over WuR-CTC Header Compression:

Profile Usage:

The SCHC over WuR-CTC Profile leverages the SCHC C/D (Compression/Decompression) mechanism, as detailed in Section 4.2. This profile ensures efficient compression of IPv6 packet headers over WuR-CTC, enhancing the overall communication efficiency.

Compression Degree:

The achieved compression degree is contingent upon the predictability of traffic and the design of Compression/Decompression Rules. In practical experiments, a 40-byte IPv6 packet header can be compressed down to an 8-bit RuleID, eliminating compression residue. This level of compression is crucial for optimizing the use of WuR-CTC, which operates in resource-constrained environments.

Fallback to SCHC F/R:

In cases where the SCHC Packet size exceeds the WuR-CTC MTU (Maximum Transmission Unit) of 89 bytes, the system employs SCHC F/R (Fragmentation and Reassembly). This ensures seamless communication by breaking down larger packets into manageable fragments, allowing for successful transmission over WuR-CTC.

5.2 SCHC over WuR-CTC Fragmentation and Reassembly:

F/R Mode Selection:

The choice of the ACK-Always SCHC F/R mode aligns with the behavior of WuR-CTC, where an acknowledgment frame is sent after receiving a DATA frame. This mode enhances efficiency in the context of WuR-CTC, promoting reliable and predictable communication.

Optimal Adaptation:

The window size is strategically set to one tile, with each SCHC Fragment payload corresponding to one tile. This approach optimizes the communication process over WuR-CTC, and SCHC ACK is transmitted after each SCHC Fragment. The inclusion of SCHC ACK in a WuR-CTC ACK frame ensures synchronized communication and efficient error handling.

Retransmission Support:

The ACK-Always F/R mode supports retransmission in case of missing SCHC Fragments, triggered by Retransmission Timer (RT) expiration. This mechanism enhances the reliability of SCHC over WuR-CTC, addressing potential packet loss scenarios.

Frame Formats:

To ensure seamless integration, SCHC over WuR Fragment and ACK message formats reuse the WuR-CTC frame structure. This reuse of structure optimizes the utilization of available resources and promotes efficient communication between nodes.

5.3 SCHC Message Adaptation over WuR-CTC:

Extended Formats:

The SCHC over WuR-CTC message format extends the WuR-CTC Link Layer frame format by incorporating a 7-bit RuleID and a 1-bit FCN (Fragment Compressed Number). This extension enhances the ability to uniquely identify compression rules and manage fragmented messages, contributing to the overall effectiveness of SCHC over WuR-CTC.

Tile Size:

The determination of tile size is based on the WuR-CTC MTU minus the SCHC Fragment header size, with the potential for the last fragment to have a smaller size. This ensures that SCHC Fragments align with the communication constraints of WuR-CTC, promoting efficient data transfer.

Timer Usage:

Both sender and receiver timers from WuR-CTC are utilized as Retransmission Timer (RT) and Inactivity Timer. This efficient use of timers contributes to the reliability and responsiveness of the SCHC over WuR-CTC communication process.

5.4 SCHC over WuR-CTC Message Exchange:

Overview:

Fig. 11 illustrates the comprehensive message exchange process between two nodes supporting SCHC over WuR-CTC. This visual representation provides a clear understanding of the sequential steps involved in the communication process.

WuR-CTC Handshake:

Initiated by a WAKE frame, the 3-way handshake of WuR-CTC sets the foundation for communication, followed by ACK frames. This handshake establishes a synchronized state between nodes, preparing for the subsequent SCHC Packet transfer.

SCHC Packet Transfer:

The actual SCHC Packet transfer begins with SCHC Fragments and corresponding ACK messages confirming correct reception. This phase showcases the efficient handling of compressed and fragmented data over WuR-CTC, ensuring reliable and complete message delivery.

Retransmission:

Upon RT expiration for any lost SCHC Fragments, retransmission occurs, preventing communication breakdowns due to potential packet loss. This adaptive mechanism contributes to the robustness of SCHC over WuR-CTC.

Completion and Sleep:

The last SCHC Fragment signals the end of the communication process, confirmed by the receiver with the C bit in the SCHC ACK. A SLEEP frame exchange concludes the process, allowing both nodes to gracefully return to sleep mode, conserving energy resources in line with the low-power requirements of WuR-CTC.

6. Evaluation of SCHC over WuR-CTC profile

6.1. SCHC over WuR-CTC Testbed Implementation:

- **Components:** The testbed comprises IEEE 802.15.4 and IEEE 802.11 devices, both implementing the WuR-CTC controller (WuTx) with additional WuRx hardware.
- **Layer Functionality:** The SCHC layer provides C/D and F/R functionality, managing the WuR-CTC Link Layer by communication with the WuR-CTC Controller.

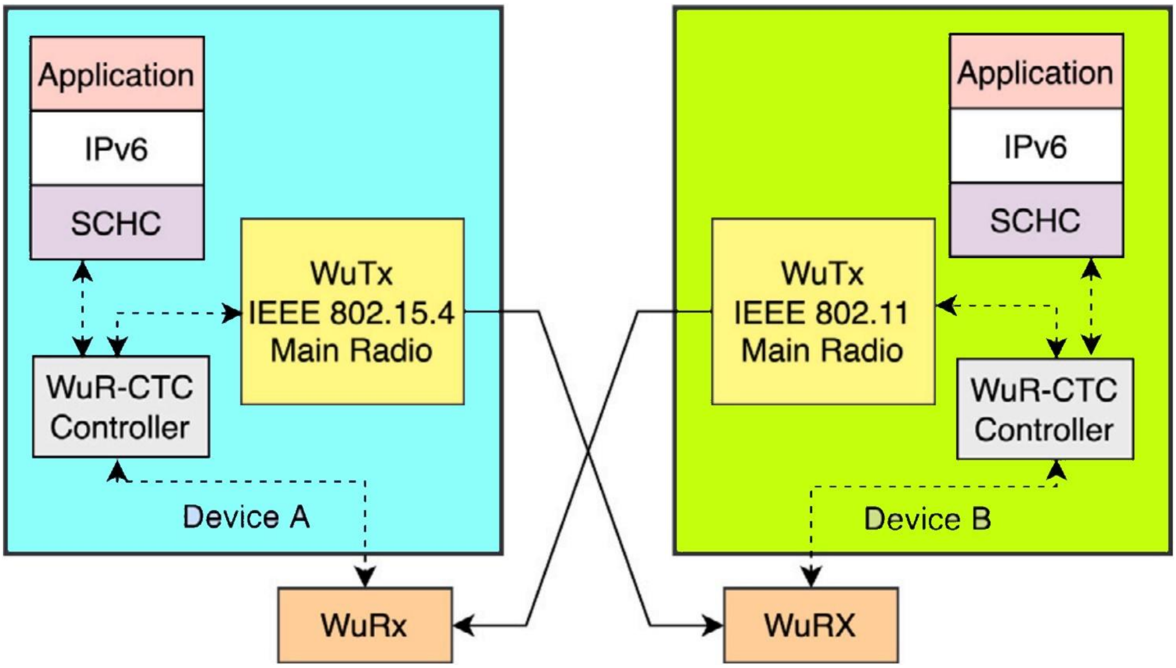

Figure 1: Architecture and Key Blocks of SCHC over Wake-Up Radio with Clear-To-Send Cancellation (WuR-CTC) Implementation. WuRx hardware is external, and SCHC handles compression, decompression, fragmentation, and reassembly of IPv6 packets with application-generated payloads.

6.2. Experimental Methodology:

- **Devices Used:** Devices include EFR32MG Mighty Gecko and ESP32 Sparkfun development kits for WuTx implementation.
- **Testbed Setup:** The testbed is placed in an indoor university environment, with devices 15 cm apart to maintain a low but non-zero error rate.
- **Scenario:** Evaluation emulates an IEEE 802.15.4 smart thermostat sending IPv6 packets to an IEEE 802.11 central controller without a gateway.
- **Parameters:** Various configurations are tested, including two different RT (Retransmission Timer) values (30 ms and 1000 ms).

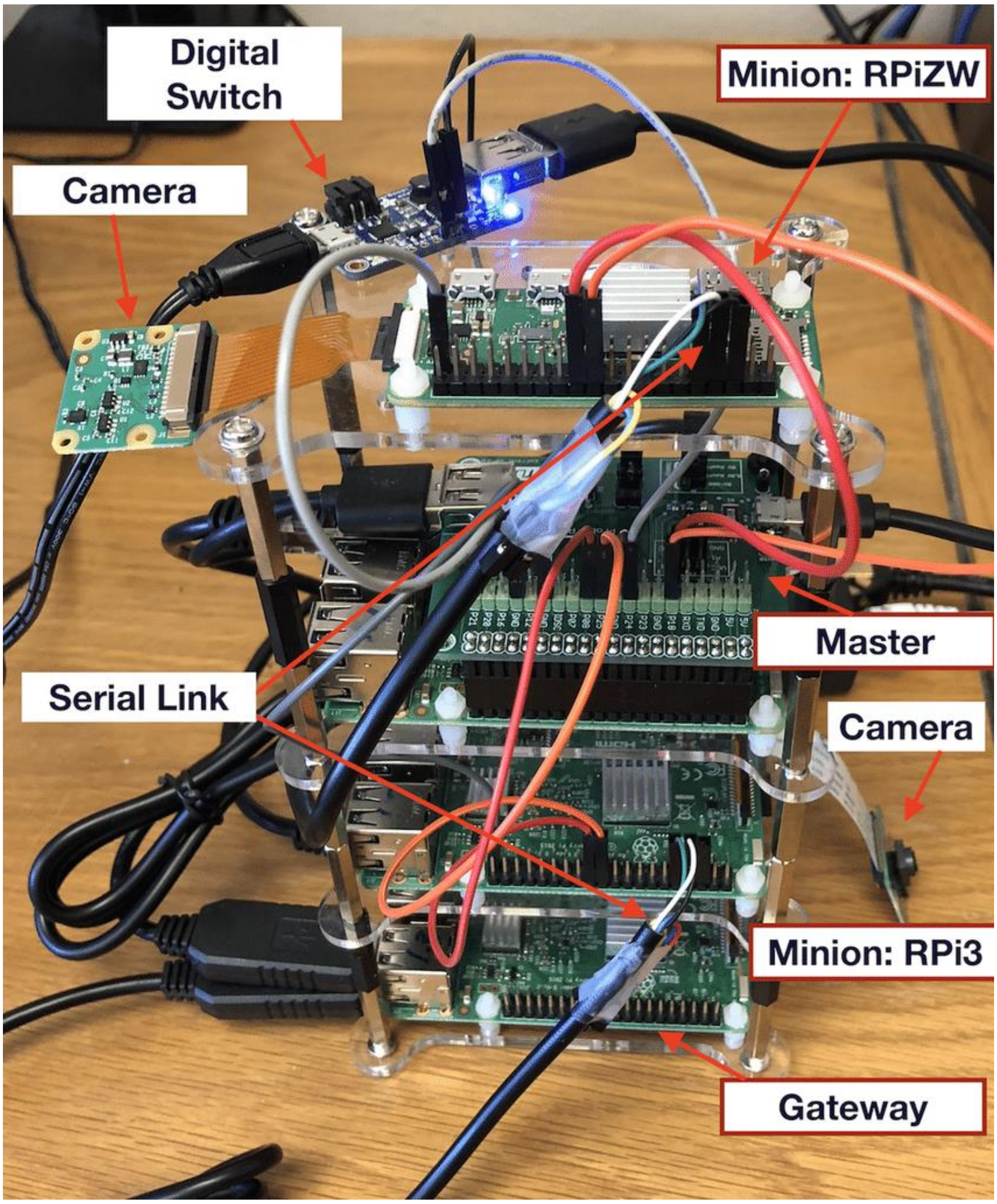

Figure 2: SCHC over Wake-Up Radio with Clear-To-Send Cancellation (WuR-CTC) Testbed Implementation with Labeled Components: Front-End Radio, Baseband Modules, IEEE 802.11 Device, and IEEE 802.15.4 Device.

6.3. Performance Metrics:

- **IPv6 Packet Compression Ratio:**
  - Highest for small IPv6 packet sizes (e.g., 127-byte) and decreases rapidly as the packet size increases.
  - 1.44 compression ratio for a 127-byte packet, dropping to 1.03 for a 1280-byte packet.

The compression ratio measures the relation between the IPv6 packet size and the SCHC Packet size. It can be calculated as follows:

$$\text{compression ratio} = \frac{\text{IPv6 packet size}}{\text{SCHC Packet Size}}. \tag{1}$$

The error rate is defined as the relation between the number of frames received (N_{FR}) and the number of frames sent (N_{FS}). It can be obtained as follows:

$$\text{error rate} = \left(1 - \frac{N_{FR}}{N_{FS}}\right) * 100. \tag{2}$$

- **Error Rate:**
    - Similar error rates for different IPv6 packet sizes.
    - Ranges between 4.3% and 6.1% for the 30-ms RT experiments.
    - Ranges between 3.6% and 5.4% for the 1000-ms RT experiments.
- **Number of Frames and Overhead:**
    - Average frames include WAKE, SLEEP, ACK, SCHC over WuR-CTC fragments, and SCHC ACK messages.
    - Overhead consists of additional bits in transmission due to various frames and headers.
    - Total ACK overhead is larger due to the 3-way handshake and acknowledgment of every SCHC over WuR-CTC fragment.
- **Transfer Time and Throughput:**
    - Transfer time is influenced by error rate, RT value, and IPv6 packet size.
    - Throughput increases linearly for small IPv6 packet sizes and decreases for larger sizes.
    - 30-ms RT provides better throughput, especially for large IPv6 packet sizes.
    - 1000-ms RT might handle burst errors but results in lower throughput values.

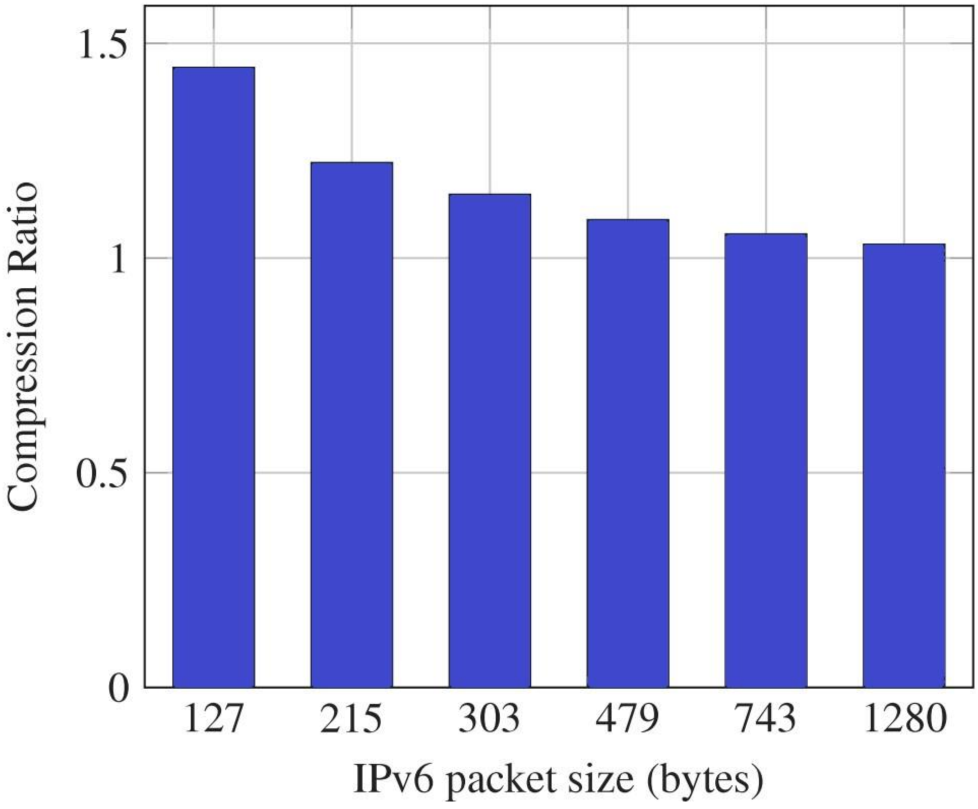

Figure 3: Compression Ratio Achieved with SCHC Header Compression in Our Implementation.

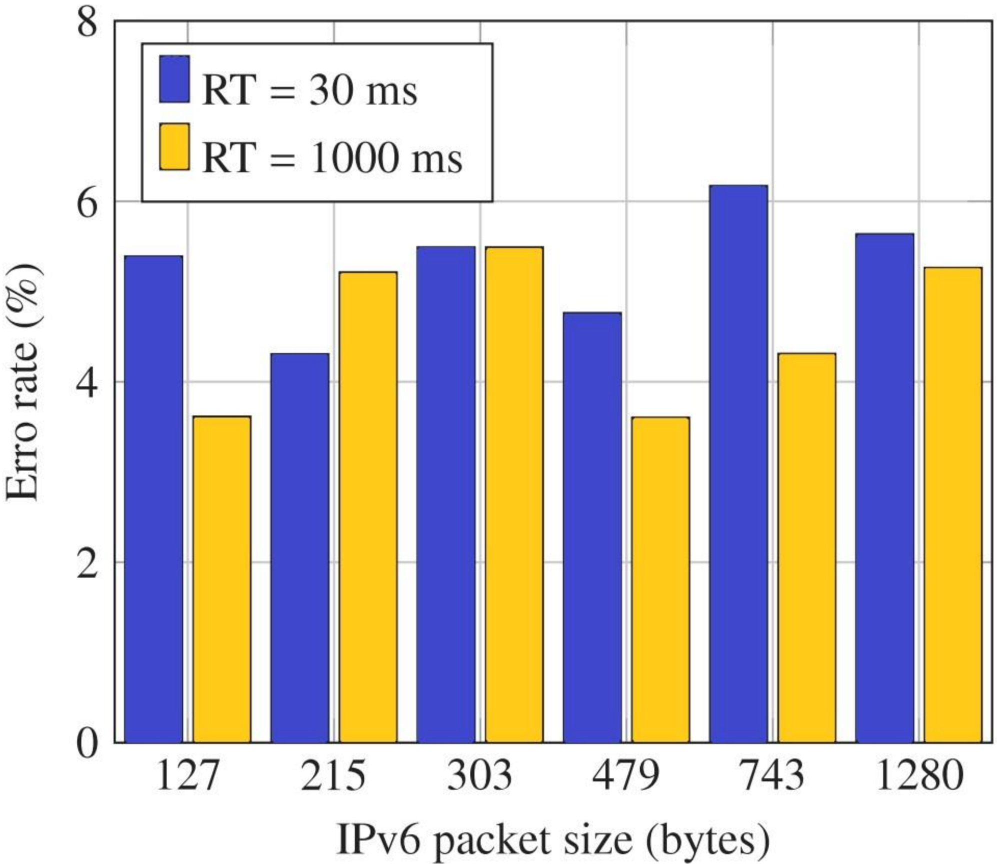

Figure 4: Relationship Between Error Rate and IPv6 Packet Size, Considering 30-ms and 1000-ms Round Trip Times (RT).

6.4. Evaluation Results:

- **Compression Ratio Trends:** Highest for small packet sizes, decreases with increasing size.
- **Error Rate:** Maintained within acceptable limits for the setup.
- **Frames and Overhead:** Acknowledgment frames contribute significantly to overhead.
- **Transfer Time:** Influenced by error rates, RT values, and packet sizes.
- **Throughput:** Better for smaller RT values, decreases for larger packet sizes.

7. CONCLUSIONS

The SCHC over WuR-CTC Profile represents a significant advancement in the realm of efficient IPv6 support, particularly noteworthy for its ability to facilitate communication without the need for a gateway. This innovation ensures seamless interoperability between devices operating under the IEEE 802.15.4 and IEEE 802.11 standards. At the core of its capabilities lies an impressive compression mechanism that reduces the IPv6 header to an incredibly compact 1 byte. This level of compression is crucial for resource-constrained environments, enabling enhanced communication efficiency.

One of the profile's standout features is the integration of the SCHC F/R ACK-Always mode with the WuR-CTC Link Layer, introducing a minimal 1-byte overhead per frame. This integration is vital for maintaining efficiency while ensuring reliability in data transfer. Leveraging ACK traffic within the WuR-CTC framework, the SCHC over WuR-CTC Profile optimizes SCHC ACKs, contributing to the enhancement of packet transfers, with support for payloads of up to 1280 bytes. Although ACK traffic introduces overhead, the profile strategically employs low Retransmission Timer values, resulting in shorter average IPv6 packet transfer times.

The design's emphasis on low-latency characteristics makes SCHC over WuR-CTC well-suited for real-time applications, particularly those involving smaller packet sizes. The efficient handling of ACK traffic and the judicious use of Retransmission Timer values showcase the profile's adaptability to diverse communication scenarios, ensuring reliable and timely data transfer. By extending the applicability of SCHC beyond Low-Power Wide-Area Networks (LPWAN), this work underscores the versatility of SCHC over WuR-CTC in addressing a broad spectrum of IPv6-based communication requirements. Overall, this profile not only optimizes IPv6 support but also paves the way for enhanced communication in scenarios where interoperability, efficiency, and real-time responsiveness are paramount.

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