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FFRDT A-MPDU: A Fragmentation-Based Selective Retransmission Scheme for IEEE 802.11n Reverse Direction Transmission

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Abstract:
IEEE 802.11n improves wireless local area network (WLAN) throughput through frame aggregation, including Aggregated MAC Protocol Data Unit (A-MPDU) transmission. A-MPDU uses Block Acknowledgment (Block ACK) to identify MPDUs that were not received successfully and to support their selective retransmission. However, when an MPDU contains a localized transmission error, retransmitting that complete MPDU can still incur avoidable overhead. This paper presents FFRDT A-MPDU, a fragmentation-based selective-retransmission scheme designed for Reverse Direction Transmission (RDT). The proposed approach divides the data carried by an aggregated transmission into smaller, separately identifiable fragments and uses an extended acknowledgment bitmap to report fragment reception status. The sender can then retransmit only fragments reported as unsuccessful, subject to the proposed protocol's modified frame and acknowledgment formats. The scheme is evaluated in NS-3 under TCP traffic, with 10–80

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stations, fragment sizes of 128–1024 bytes, and bit-error-rate (BER) settings of 10^{-4}, 10^{-5}, and 10^{-6}. The reported results show throughput values of up to approximately 127 Mbps at 10 stations under BER = 10^{-6}. At the same station count, the reported throughput is approximately 60 Mbps and 90 Mbps under BER = 10^{-4} and 10^{-5}, respectively. For the 256-byte setting and BER = 10^{-5}, the reported delay increases from approximately 5 ms at 10 stations to 37 ms at 80 stations. These results suggest that fragment-level selective retransmission can improve performance in the evaluated scenarios. The interpretation of these results is limited by the simulation configuration and statistical details that must be reported explicitly; the proposed extended acknowledgment format also requires protocol-level modification and is not presented as an unmodified IEEE 802.11n feature.

Keywords: IEEE 802.11n, A-MPDU, Block ACK, fragmentation, selective retransmission, Reverse Direction Transmission, NS-3.

FFRDT A-MPDU : آلية لإعادة الإرسال الانتقائي القائمة على التجزئة في تقنية الإرسال العكسي للاتجاه وفق معيار IEEE 802.11n

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الملخص

يُسهم معيار IEEE 802.11n في تحسين معدل نقل البيانات في الشبكات المحلية اللاسلكية (WLAN) من خلال تقنية تجميع الإطارات، بما في ذلك إرسال وحدات بيانات بروتوكول التحكم في الوصول إلى الوسيط المجمّعة (A-MPDU). وتعتمد هذه التقنية على آلية الإقرار الكتلي (Block Acknowledgment – Block ACK) لتحديد وحدات

بيانات بروتوكول التحكم في الوصول إلى الوسيط (MPDUs) التي لم يتم استقبالها بنجاح، ودعم إعادة إرسالها بصورة انتقائية. ومع ذلك، عندما يحتوي أحد إطارات MPDU على خطأ في جزء محدد من عملية الإرسال، فإن إعادة إرسال إطار MPDU بالكامل قد تؤدي إلى زيادة غير ضرورية في العبء الإضافي على الشبكة.

تقدم هذه الورقة البحثية آلية FFRDT A–MPDU، وهي آلية لإعادة الإرسال الانتقائي القائمة على التجزئة، ومصممة خصيصًا لتقنية الإرسال العكسي للاتجاه (Reverse Direction Transmission – RDT). وتعتمد الآلية المقترحة على تقسيم البيانات المنقولة ضمن الإرسال المجمّع إلى أجزاء أصغر، بحيث يكون لكل جزء معرّف مستقل يتيح تمييزه وتتبع حالة استقباله. كما تستخدم الآلية خريطة بتات موسّعة للإقرار (Extended Acknowledgment Bitmap) للإبلاغ عن حالة استقبال كل جزء. وبناءً على ذلك، يصبح بإمكان المرسل إعادة إرسال الأجزاء التي تم الإبلاغ عن عدم استقبالها بنجاح فقط، وذلك وفقًا لصيغ الإطارات وآلية الإقرار المعدّلة التي يقترحها البروتوكول.

تم تقييم الآلية المقترحة باستخدام المحاكي الشبكي NS–3 في ظل حركة مرور تعتمد على بروتوكول التحكم في الإرسال(TCP) ، وبأعداد من المحطات تتراوح بين 10 و80 محطة، وأحجام تجزئة تتراوح بين 128 و1024 بايت، مع اعتماد قيم مختلفة لمعدل خطأ البتات(Bit Error Rate – BER) ، وهي (10^{-4})و (10^{-5}) و(10^{-6}). أظهرت النتائج المبلّغ عنها تحقيق معدل نقل بيانات يصل إلى نحو 127 ميغابت في الثانية عند استخدام 10 محطات، وبمعدل خطأ بتات قدره (10^{-6}). وفي ظل العدد نفسه من المحطات، بلغ معدل نقل البيانات نحو 60 ميغابت في الثانية و90 ميغابت في الثانية عند استخدام معدلي خطأ بتات قدرهما (10^{-4}) و(10^{-5}) ، على التوالي. أما بالنسبة إلى حجم التجزئة البالغ 256 بايت، وعند معدل خطأ بتات قدره (10^{-5})، فقد أظهرت النتائج ارتفاع زمن التأخير من نحو 5 مللي ثانية عند وجود 10 محطات إلى 37 مللي ثانية عند وجود 80 محطة.

تشير هذه النتائج إلى أن استخدام آلية إعادة الإرسال الانتقائي على مستوى الأجزاء المجزأة يمكن أن يسهم في تحسين أداء الشبكة ضمن سيناريوهات التقييم التي تمت دراستها. ومع

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ذلك، فإن تفسير هذه النتائج يظل مرتبطًا بإعدادات المحاكاة والتفاصيل الإحصائية التي ينبغي توضيحها والإبلاغ عنها بصورة صريحة. كما أن صيغة الإقرار الموسّعة المقترحة تتطلب إجراء تعديلات على مستوى البروتوكول، ولا تُعد جزءًا من الخصائص القياسية غير المعدّلة لمعيار IEEE 802.11n.

الكلمات المفتاحية: IEEE 802.11n، وحدات بيانات بروتوكول التحكم في الوصول إلى الوسيط المجمّعة(A-MPDU) ، الإقرار الكتلي(Block ACK) ، التجزئة (Fragmentation)، إعادة الإرسال الانتقائي(Selective Retransmission) ، الإرسال العكسي للاتجاه(Reverse Direction Transmission) ، المحاكي الشبكي NS-3.

1. Introduction

Reverse Direction (RD) transmission in IEEE 802.11 allows a TXOP holder to grant its peer an opportunity to transmit data during the remaining TXOP, reducing the need for a new channel-access procedure for every reverse-direction exchange. The initiator obtains the TXOP and may issue a Reverse Direction Grant (RDG); the responder can then transmit one or more PPDUs in the granted opportunity. A Block ACK or ACK may be included as part of the exchange, depending on the applicable acknowledgment procedure [1], [2]. Figure 1 illustrates the reverse-direction exchange considered in this study. The proposed work focuses on combining this exchange opportunity with fragment-level selective retransmission.

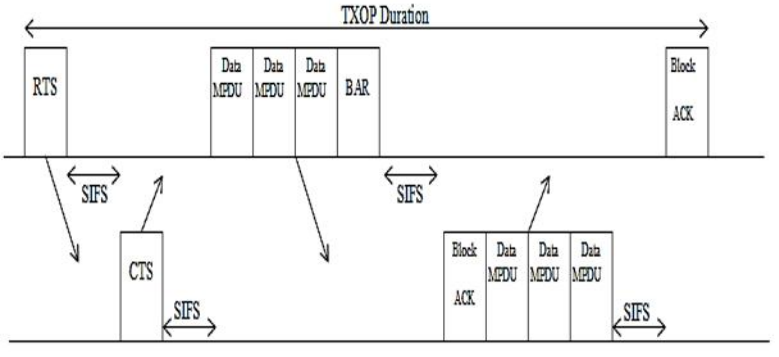


Figure 1: Reverse direction transmission with A-MPDU

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1.2 A-MPDU aggregation

A-MPDU aggregation combines multiple MPDUs into one aggregate transmitted within a PPDU. Each MPDU retains its own MAC header and Frame Check Sequence (FCS), and delimiter and padding information are used to separate MPDUs in the aggregate. A-MPDU therefore supports selective retransmission at the MPDU level: the Block ACK bitmap identifies MPDUs received successfully and those requiring retransmission. It is inaccurate to state that a single MPDU error necessarily causes retransmission of the entire A-MPDU. The motivation for FFRDT is narrower: when a portion of the payload within an MPDU is corrupted, the standard MPDU-level acknowledgment mechanism does not, by itself, acknowledge arbitrary sub-MPDU fragments independently. FFRDT proposes an additional fragment-level mechanism for this case. Any extended bitmap or modified acknowledgment format described below is a proposed protocol extension, not a claim about the unmodified IEEE 802.11n Block ACK format [3]–[5].

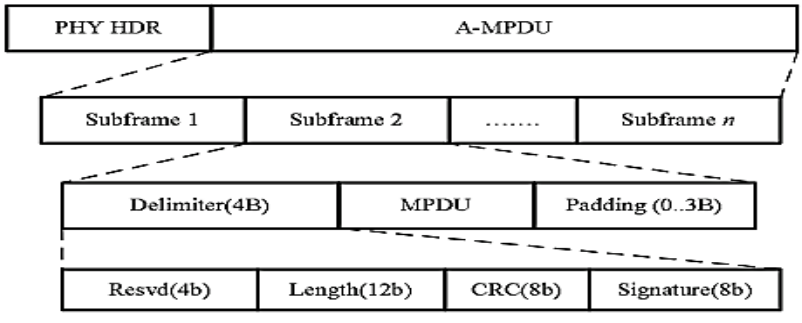


Figure 2: A-MPDU frame structure

1.3 Sequence of Reverse Direction (RD) exchange

A typical RD exchange proceeds as follows:

a) The TXOP holder (RD initiator) transmits an RDG PPDU that grants the peer station an opportunity to transmit during the remaining TXOP. The RDG/More PPDU subfield indicates whether the exchange continues [6].

b) The peer station (RD responder) transmits one or more PPDUs during the granted interval. An acknowledgment may be piggybacked where permitted by the applicable exchange

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procedure. The responder's final PPDU indicates the end of its response burst [7], [8].

c) The RD initiator completes the exchange by transmitting the final PPDU and the required ACK or Block ACK response, as applicable [2], [9].

A TXOP may contain more than one RD exchange sequence, subject to the standard's exchange rules and the capabilities of the participating stations [1], [10].

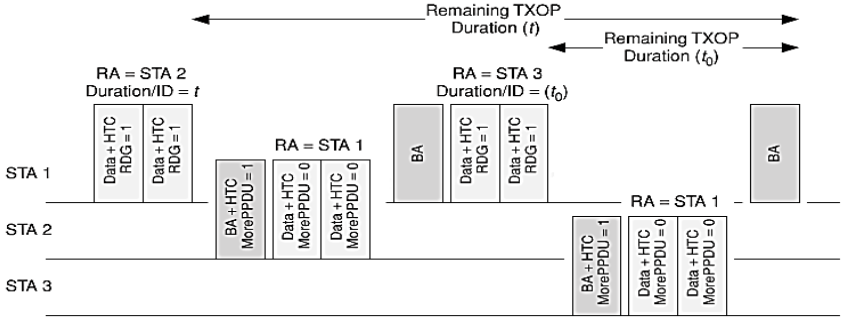


Figure 3: Reverse Direction exchange

2. System design

2.1 FFRDT A-MPDU scheme description

The proposed FFRDT A-MPDU scheme divides the data carried by an aggregate into smaller fragments, assigns each fragment an identifier, and transmits the fragments as part of the aggregate. The receiver checks each fragment using the integrity-checking mechanism defined for the implementation and records its reception status. The receiver then returns an acknowledgment bitmap in which each bitmap position corresponds to one fragment. The sender uses this feedback to retransmit only fragments marked as unsuccessful, rather than retransmitting the complete containing MPDU. This description distinguishes the proposed fragment-level operation from standard A-MPDU Block ACK, which provides selective retransmission at the MPDU level.

The one data frame is 8,192 bytes and that eight such frames are aggregated. These figures imply an aggregate payload of 65,536 bytes (8 × 8,192), before any additional headers, delimiters, padding, or other overhead. The separate value of 56,536 bytes

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appearing in the simulation description cannot be reconciled from the information currently provided.

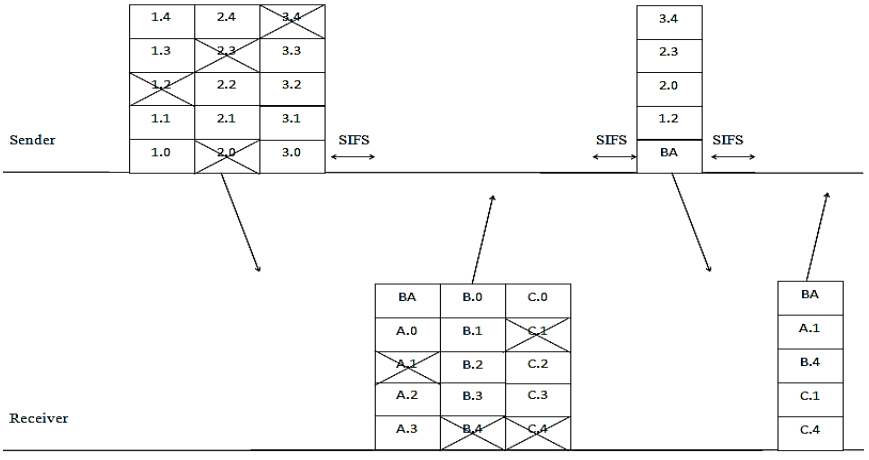


Figure 4: FFRDT A-MPDU Scheme

2.2 Research gap and novelty

Standard A-MPDU already provides MPDU-level selective retransmission through Block ACK; therefore, the research gap is not the absence of error recovery in A-MPDU. The limitation addressed here is the granularity of the acknowledgment and retransmission unit. When an error affects only part of an MPDU, an ordinary Block ACK reports the status of the MPDU, not independently identified sub-MPDU fragments. FFRDT explores fragment-level status reporting within an RD exchange so that successfully received fragments need not be sent again when only other fragments are corrupted. The distinction among the mechanisms evaluated in this paper is as follows: (i) DCF represents contention-based channel access; (ii) BA represents the baseline Block ACK/A-MPDU mechanism with MPDU-level acknowledgment; (iii) RD represents the baseline Reverse Direction transmission procedure; and (iv) RD-MFF is an existing comparison method (Reverse Direction Multi-Frame), not the proposed FFRDT scheme. FFRDT is the proposed fragmentation-based selective-retransmission method. The claimed contribution is the integration of fragment identification, fragment-status feedback, and selective

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fragment retransmission into the reverse-direction exchange. This contribution requires a modified fragment format and an extended acknowledgment representation; it should not be described as an already-standardized IEEE 802.11n feature.

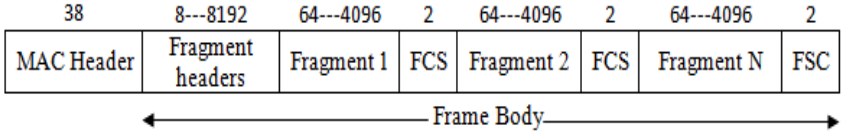


Figure 5: Proposed FFRDT A-MPDU fragment and aggregate frame format

The proposed acknowledgment bitmap is described as 128 bytes, which equals 1,024 bits. If the protocol assigns exactly one bitmap bit to each fragment, this field can represent at most 1,024 fragments. A capacity of 512 fragments would use only 512 of the 1,024 available bits; the manuscript must explain whether the remaining bits are reserved, unused, or assigned another purpose. The current text alternates between 512 and 1,024 fragments and must not do so. For consistency, the scheme description in this revision uses the direct one-bit-per-fragment interpretation (1,024 bits = 1,024 fragment-status entries).

This 128-byte bitmap is an extended, proposed acknowledgment field. It is not the ordinary compressed Block ACK bitmap defined for IEEE 802.11n. Interoperability with unmodified stations cannot be assumed: both transmitter and receiver must implement the same extended frame format, agree on the fragment numbering and bitmap length, and parse the added field.

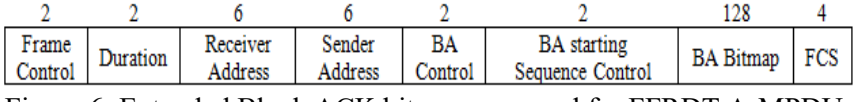


Figure 6: Extended Block ACK bitmap proposed for FFRDT A-MPDU

In the reverse-direction response, the receiver reports fragment reception status in the proposed extended bitmap. The receiver maintains fragment-reassembly state in the receiver queue (Rq), indexed by the aggregate and fragment identifiers. Successfully received fragments are retained until the complete data unit can be

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reassembled; fragments that fail the integrity check are marked as missing and requested again. A fragment is delivered to the upper layer only after the complete data unit has been reassembled and its integrity has been verified. The sender retains the corresponding fragments in the sender queue (Sq) until their successful reception is acknowledged.

2	2	6	6	2	2	128	4	38	8---8192	64---4096	2	64---4096	2	64---4096	2
Frame Control	Duration	Receiver Address	Sender Address	BA Control	BA Starting Sequence Control	BA Fragment Bitmap	FCS	MAC Header	Fragment headers	Fragment 1	FCS	Fragment 2	FCS	Fragment N	FSC

Figure 7: FFRDT A-MPDU reverse-direction acknowledgment frame

2.3 Sender and receiver procedures

Sender procedure: (1) divide the data unit into fragments according to the configured fragment size; (2) assign a unique fragment index within the aggregate and retain the fragment in Sq; (3) transmit the aggregate during the permitted RD exchange; (4) receive and validate the acknowledgment frame and its bitmap; (5) map each bitmap bit to the corresponding fragment index; (6) remove acknowledged fragments from Sq; and (7) retransmit only fragments reported as missing, subject to the retry and TXOP limits implemented by the simulator.

Receiver procedure: (1) identify the aggregate and fragment index from each received fragment; (2) verify the fragment using the implemented integrity check; (3) store valid fragments in Rq and mark invalid or absent fragments as missing; (4) handle out-of-order arrivals by storing fragments according to their identifiers rather than their arrival order; (5) construct the acknowledgment bitmap using the agreed one-bit-per-fragment mapping; (6) transmit the acknowledgment in the reverse-direction exchange; and (7) reassemble and deliver the data unit only when all required fragments have been received and the reassembled data passes integrity verification.

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Table 1. FFRDT field specification

Field	Size	Function
Aggregate identifier	Not specified in the source	Associates fragments with the correct aggregate.
Fragment identifier/index	Not specified in the source	Identifies the fragment position and supports out-of-order reassembly.
Fragment payload	Configured fragment size (128–1,024 bytes in the reported experiments)	Carries a portion of the original data unit.
Integrity check/FCS	Not specified in the source	Detects corruption in the received fragment. The exact integrity-check mechanism must be stated; the source does not establish whether a separate FCS is present for every fragment.
Extended acknowledgment bitmap	128 bytes (1,024 bits), as claimed in the manuscript	Reports fragment reception status if one bit is assigned to each fragment. The bit-to-fragment mapping, bit order, and treatment of unused bits must be specified.
Starting sequence control	Standard field; exact use in the proposed extension must be stated	Associates the acknowledgment with the relevant transmission/sequence context.

2.4. Specification of the Proposed Fragment and Acknowledgment Fields

Table 2 summarizes the fields required by the proposed FFRDT A-MPDU description. The 128-byte bitmap contains 1,024 bits; it can acknowledge up to 1,024 fragments only if one bit is assigned to each fragment. A 512-fragment configuration would use 512 bits and leave the remaining 512 bits unused or reserved, which must be specified by the protocol implementation.

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Table 2: Proposed FFRDT A-MPDU field specification

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Aggregate identifier	Not specified in the source	Associates fragments with the correct aggregate.
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Fragment payload	Configured fragment size (128–1,024 bytes in the reported experiments)	Carries a portion of the original data unit.
Integrity check/FCS	Not specified in the source	Detects corruption in the received fragment; the exact mechanism must be stated. The manuscript does not establish whether a separate FCS is present for every fragment.
Extended acknowledgment bitmap	128 bytes (1,024 bits), as claimed in the manuscript	Reports fragment reception status if one bit is assigned to each fragment. The mapping, bit order, and reserved-bit behavior require specification.
Starting sequence control	Standard field; exact use in the proposed extension must be stated	Associates the acknowledgment with the relevant transmission/sequence context.

3. Results and analysis

The proposed scheme is evaluated against DCF, BA, RD, and RD-MFF. RD-MFF denotes the existing Reverse Direction Multi-Frame comparison method; it is not another name for FFRDT. The reported experiments vary the fragment size, the number of stations, and the bit error rate (BER). Table 3 is intended to summarize the NS-3 configuration.

Table 3: NS-3 simulation parameters

Parameters	value
Number of Stations	50, Varied
Application Rate	N/A
Data Rate	648 Mbps
Basic Rate	54 Mbps
Packet Size	1024 Bytes
DCF Frame Size	1024 Bytes
FFRDT, BA, RD Frame Size	56536 Bytes
FFRDT Subframe Size	Varied
Protocol	TCP

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The throughput results are presented in Figure 8 as a function of fragment size. At BER = 10^{-4}, the reported throughput values for the proposed method are approximately 45 Mbps at 128 bytes and 47.2 Mbps at 256 bytes. At BER = 10^{-5}, the corresponding values are approximately 75 Mbps and 77 Mbps; at BER = 10^{-6}, they are approximately 110 Mbps and 111.4 Mbps. The unit for throughput is Mbps, not bytes.

3.1 TCP traffic evaluation

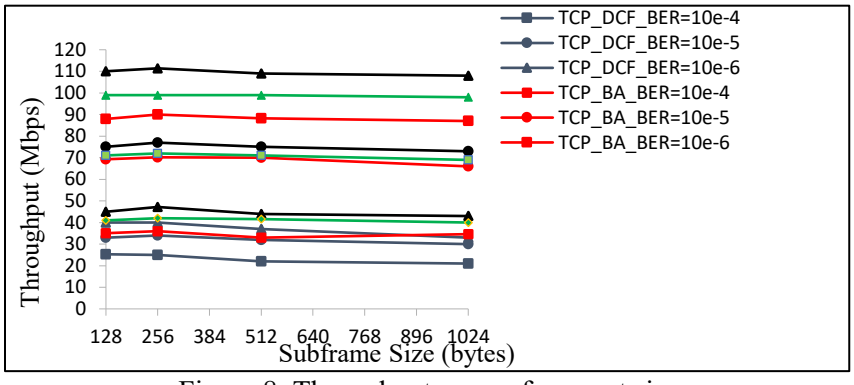


Figure 8: Throughput versus fragment size

Figure 9 presents throughput as the number of stations increases, with the fragment size set to 256 bytes. At 10 stations, the reported FFRDT throughput is approximately 60 Mbps at BER = 10^{-4}, 90 Mbps at BER = 10^{-5}, and 127 Mbps at BER = 10^{-6}. Throughput decreases as the number of contending stations increases, consistent with increased contention and collision probability. The stated percentage gains over RD should be recalculated directly from the plotted data and should identify the exact station range over which each percentage applies.

Figure 10 compares delay for different fragment sizes at BER = 10^{-5}. The reported FFRDT delay increases from approximately 0.013 s at a fragment size of 128 bytes to approximately 0.090 s at 1,024 bytes. The corresponding delay values for the comparison methods are shown in the figure. Smaller fragments may reduce the amount of data retransmitted after a localized error, but they also increase the number of fragment headers and acknowledgment bits;

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therefore, the observed delay trend should be interpreted together with protocol overhead.

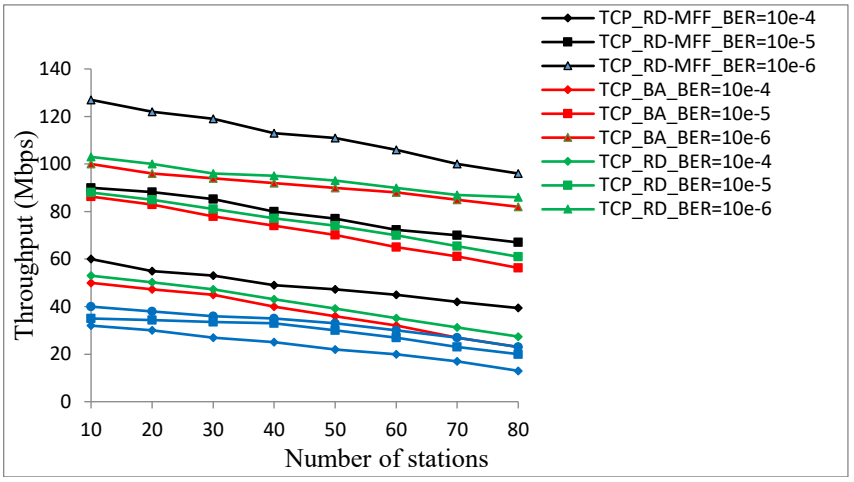


Figure 9: Throughput versus number of stations

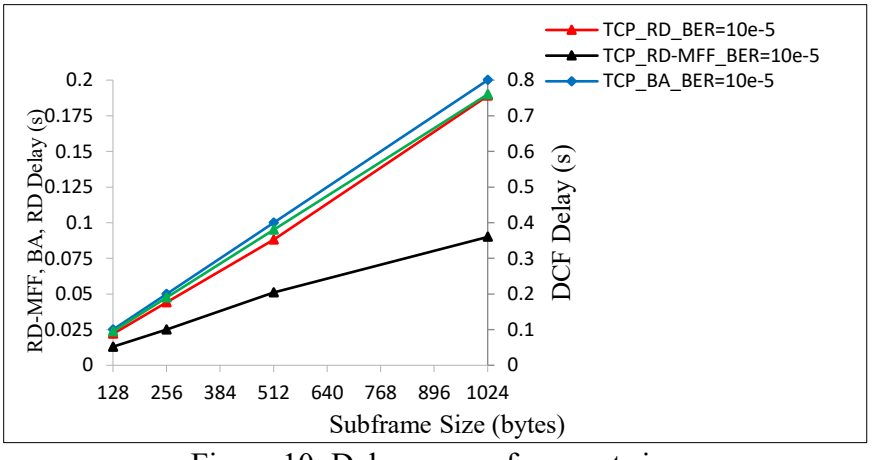


Figure 10: Delay versus fragment size

Figure 11 presents delay as the number of stations increases, using a fragment size of 256 bytes and BER = 10^{-5}. The reported FFRDT delay is approximately 0.005 s at 10 stations and 0.037 s at 80 stations. Delay increases with the number of stations, indicating the effect of contention and increased channel-access time.

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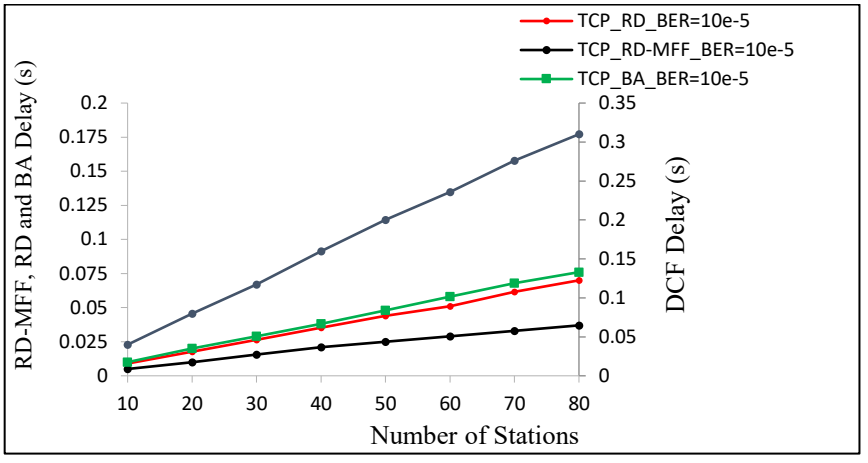


Figure 11: Delay versus number of stations

3.2 Simulation reproducibility and statistical validation

The information currently available in the paper identifies NS-3, TCP traffic, 10–80 stations, fragment sizes of 128–1,024 bytes, and BER values of 10^{-4}, 10^{-5}, and 10^{-6}. It does not identify the NS-3 release, channel/propagation model, channel bandwidth, PHY mode and number of spatial streams, MIMO configuration, TCP variant and parameters, simulation duration, warm-up interval, number of independent repetitions, random seed/run numbers, or the precise throughput and delay measurement intervals.

3.3 Overhead, performance metrics, and limitations

Fragment-level retransmission can reduce retransmitted payload when errors are localized, but the gain is not free. Each fragment requires identification information and integrity protection, while the extended bitmap increases acknowledgment size and processing work. Smaller fragments increase the number of headers and bitmap entries per original data unit; larger fragments reduce this overhead but may require more data to be retransmitted after an error. The balance depends on BER, fragment size, aggregate size, and station contention. This paper reports throughput and delay only. It does not provide measured retransmission rate, packet delivery ratio, fairness, or a quantitative overhead breakdown; these metrics must not be claimed as experimentally demonstrated until they are measured and added. Potential limitations include the additional

header and bitmap overhead, processing and memory required for fragment tracking and reassembly, the need for both endpoints to support the modified acknowledgment format, and reduced benefit when errors are rare or when fragment-level signaling costs exceed the saved retransmission airtime. Performance may also deteriorate under heavy contention, high acknowledgment loss, fragment-header corruption, or very small fragment sizes.

4. Conclusion and Future work

This paper presents FFRDT A-MPDU, a proposed fragmentation-based selective-retransmission scheme for IEEE 802.11n Reverse Direction Transmission. Unlike standard A-MPDU Block ACK, which identifies successful and unsuccessful MPDUs, the proposed method aims to report reception status at the fragment level and retransmit only missing or corrupted fragments. In the reported NS-3 results, throughput reaches approximately 127 Mbps at 10 stations under BER = 10^{-6}, while the reported delay for a 256-byte fragment size and BER = 10^{-5} increases from approximately 5 ms at 10 stations to 37 ms at 80 stations. These values indicate potential benefits under the evaluated conditions, but they do not establish universal improvement. The method introduces additional fragment-header, bitmap, processing, and interoperability costs, and its benefit depends on the error rate, fragment size, and network load. The current paper does not provide repeated-run statistics or measurements of retransmission rate, packet delivery ratio, fairness, and total protocol overhead. Future work should evaluate these conditions, quantify overhead and retransmission rate, report packet delivery ratio and fairness, and validate the extension with independent simulation runs and, where possible, an implementation testbed.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The datasets were generated through NS-3-based simulation experiments conducted to evaluate the performance of the proposed FFRDT A-MPDU scheme under different subframe sizes, numbers of stations, and bit error rate (BER) conditions. The available data include the simulation parameters, performance measurements, and results underlying the throughput and delay analyses reported in this manuscript. The simulation data and related files can be provided for research and verification purposes upon reasonable request, subject to any applicable institutional or ethical restrictions.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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