Pub/Sub in the Air: A Novel Data-centric Radio Supporting Multicast in Edge Environments[1]

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Abstract

V-MAC is a novel data-centric radio that provides a pub/sub (publish/subscribe) abstraction to replace the point-to-point abstraction in existing wireless radios. Its purpose is to support robust, scalable, and high-rate multicast in edge environments, where peer communication among mobiles, vehicles, IoT, and drones is frequently data-centric. V-MAC filters frames by data names instead of MAC addresses, thus eliminating complexities and latencies in neighbor discovery and group maintenance in existing radios. It enables receiver-initiated pub/sub communication, achieving on-the-fly binding and making prior discovery or determination of destination group or node addresses unnecessary. Based on this system, a series of experiments on packet loss rate and transmission rate were conducted in this project. Furthermore, based on the MAC layer logic, the project attempted to design and extend the UDP transmission mechanism of the ICN layer to provide an application layer interface and to connect to the V-MAC layer. The re-occurrence of the original paper was done in preparation for implementing a network application system compatible with ICN in the future.

Keywords： Wireless edge Communication, data-centric networks, multicast, MAC protocol.

1 Introduction

The emergence of edge computing has led to the creation of dynamic and data-centric one-to-many communication that allows peer communication between mobiles, vehicles, IoT and drones. However, the wireless technologies in use, such as WiFi, DSRC, and V2X, have limitations when it comes to dynamic and data-centric communication. The use of address-based, point-to-point abstraction in these technologies requires a priori static binding, leading to complexity and latency that are not suitable for dynamic edge environments. The lack of support for robust multicast is another drawback of current wireless technologies. To eliminate these drawbacks, a pub/sub abstraction can be used at the wireless MAC layer to enable late and on-the-fly binding, allowing each neighbor to decide whether and how to respond based on desired data attributes. Elbadry proposed a data-centric radio, V-MAC, that uses the pub/sub abstraction to eliminate the need, complexity, and latency in discovery and management of groups and nodes, including beacons, group formations, and address translations. The system provides a pub/sub abstraction to replace the point-to-point abstraction used in existing wireless radios. V-MAC filters frames by data names, thus eliminating complexities and latencies in neighbor discovery and group maintenance. The system supports robust, scalable, and high-rate multicast with consistently low losses across receivers of varying reception qualities. Elbadry had also proposed a data-oriented acknowledgment mechanism and contributes to making V-MAC a mature, low-cost, reusable research asset readily adoptable by the community. The V-MAC prototype has been tested and validated on 4 major WiFi chipsets and 10 different commodity 802.11 a/b/g/n/ac radios and offers significant improvements over existing wireless technologies in highly dynamic edge environments.

In this paper reproduction, we attempted to run the original system on the Raspberry Pi prototype as described in the original paper, removed the MAC and IP layers of the network protocol stack, allowing user programs to communicate directly with the V-MAC layer. We then used this program for experimental evaluation to compare the differences between our current environment and the original paper environment. Finally, on the system running V-MAC, a custom user datagram layer was implemented to realize a UDP-like protocol layer.

2 Related works

2.1 Publish/Subscribe

Pub/sub is an asynchronous communication abstraction used widely in social media (e.g., Twitter, Facebook) and business integration[2][3][4][5][6][7][8][9]. It decouples sender/receivers: receivers (consumers) specify desired data in subscriptions using hierarchical topic names, multi-dimensional attribute predicates or queries like XPath. Senders’ (producers) publications are matched against subscriptions at intermediaries (i.e., brokers) and delivered accordingly. Most pub/sub systems are built at application layer, and utilize point-to-point transport/networks (e.g., TCP/IP). V-MAC adopts this abstraction and is the first to offer it at the MAC layer.

2.2 Information Centric Networking

Among ICN proposals, NDN[10][11][12] is probably the most prominent. It takes a similar pub/sub abstraction and has been tested for video transmission[13] and vehicular networking[14][15][16] on top of and thus limited by WiFi ad hoc broadcast (e.g., lowest base rate, high loss). V-MAC pushes the pub/sub abstraction down to the MAC. It eliminates complexities in address-based WiFi stacks (e.g., unnecessary queues and en/decapsulations, beacons, group formation). V-MAC completes a full data-centric stack, which will benefit many edge applications (e.g., vehicles, drones, IoT and mobile[17][18][19][20][21][14][22][23][24]).

2.3 WiFi Multicast

Three common techniques have been explored for robust, low loss, address-based WiFi multicast: automatic retransmission request (ARQ) to trigger retransmission of missed frames[25][26][27][28][29][30]; forward error correction (FEC)[31] to reconstruct the content despite losses[32][33][34][35][36][37][38][39]; and network coding[40] to reduce the number of transmissions[41].

Some ARQ based designs adopt collective feedback[30][42][43][44][28][45]). V-MAC utilizes a similar principle, but applied under a completely different pub/sub abstraction for highly dynamic edge environments. Those designs do not modify and rely on WiFi’s point-to-point abstraction, thus they cannot eliminate the baggage of address/group discovery and formation. FEC and network coding are orthogonal techniques that V-MAC can also adopt.

2.4 Vehicular Networking

Dedicated Short-Range Communication (DSRC)[46][47][48] uses 802.11p (a variant of 802.11a) as MAC/-PHY. Despite decades-long standardization, significant safety and throughput weaknesses still exist[49][50][51][52][53]. V-MAC provides a new pub/sub abstraction and robust, high rate multicast, features needed for vehicles but lacking in 802.11p.

3 Method

3.1 Overview

Our goal for this project is to replicate the system, evaluate its performance, and design a UDP-like protocol as an ICN layer under our own hardware environment and experimental conditions.

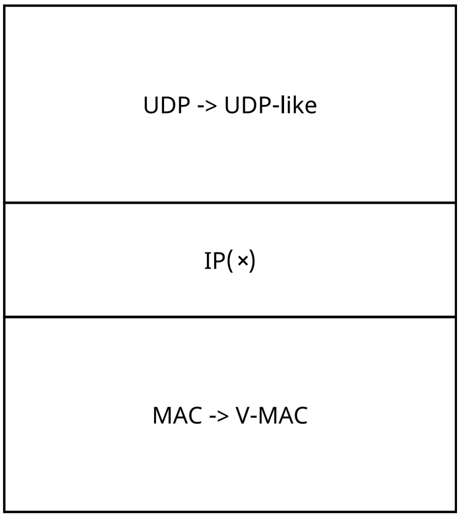


Figure 1: Overview of the protocol stack change

3.2 Data-Centric Frame Filtering

V-MAC works with ICN to filter incoming frames by name. To request desired data, a consumer's ICN layer sends an Interest packet carrying that data's name. V-MAC converts it into an Interest frame, passing it to the PHY for transmission, and records the data name. A neighbor that has that data sends back Data packets. Since a Data packet can be many MTU sizes, a link protocol between ICN and V-MAC breaks it into multiple MTU size units, and V-MAC converts each into a Data frame, carrying the same data name but a different sequence number denoting its position within the packet. The consumer's V-MAC receives and matches incoming Data frame's names against recorded names of desired data. Only frames of matching names are passed up to the ICN layer. The LP reassembles such frames into one Data packet when needed.

Therefore, the UDP-like ICN layer we design should have the naming and fragmentation functions to meet the needs of V-MAC. We need to perform fragmentation and reassembly of large data at this layer, with each frame size designed to be 1024B. And complete a basic naming scheme, for example, we name the data according to the first 8 bytes of the transmitted content.

3.3 Robust Multicast

To support robust multicast, Elbadry developed an efficient, scalable, data-oriented acknowledgment (DACK) aggregated over multiple receiver-frames. A sender transmits multiple data frames back to back. It uses one preamble to transmit each frame, thus one synchronization error loses only one frame. This also allows other radios to compete and grab the medium, making it fair game instead of monopolizing the medium for lengthy periods.

In our paper reproduction, to verify the above functions, we need to conduct one-to-many transmission experiments, including text content and video streaming. We plan to use four Raspberry Pis, one as the producer and the other three as consumers. During the experiment, we will record the total time of transmission, the total number of frames received by the receivers, to calculate the packet loss rate and transmission speed.

4 Implementation details

4.1 Running V-MAC on our raspberry pi

We used Raspberry Pi 4B as the hardware and Alfa AWUS036NHA as the WiFi dongle. Initially, we used Linux kernel version 4.19.97v7l, a 32-bit system as described in the original paper. However, to ensure stable operation in future projects, we also ran the system on a 64-bit Raspberry Pi system running Linux kernel version 5.10v8. We recompiled the V-MAC module and modified the ieee80211csaiscomplete function in the ath9k module to allow for proper V-MAC construction.

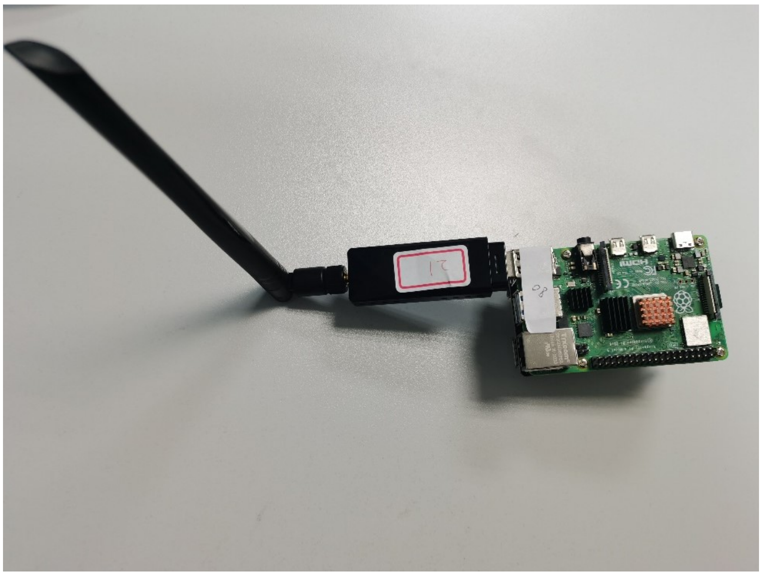


Figure 2: Raspberry with WiFi Dongle

4.2 UDP-like protocol design

To implement an ICN layer protocol, we designed the following steps: First, design the data structure of a single data packet. Each packet should have a ”next” and ”prev” pointer. When a large application data is received, it will be fragmented, and each piece will be allocated a data packet structure and linked together with pointers to form a doubly-linked list. The data structure also includes ”head” and ”tail” pointers in the payload section, which can remove the V-MAC and PHY headers by moving pointers. The structure must also have a name field, and we specify that the first byte of the data packet stores the packet type and the length of the packet name, so that the name can be parsed when the packet is received. Second, we should implement the send buffer and receive buffer, establish channels between the upper layer data and this layer, and the channel between this layer and V-MAC. Since the network card will interrupt to notify V-MAC for processing after receiving information, the transmission channel between this layer and V-MAC should be blocking to obtain data in real-time, while the upper channel can be non-blocking to improve efficiency. Finally, we must consider whether this layer protocol is implemented in user space or as a kernel module in kernel space. The former is easier to debug and run, but requires a large amount of code refactoring. The latter is difficult to debug but can use existing kernel functions and data structures. We tried both methods and decided to implement the basic functions in user space first and then move to the kernel level to make it a part of the protocol stack.

4.3 Evaluation environment setup

We used four Raspberry Pi devices in total for our experimental evaluation, one as a producer and the other three as consumers. The first experiment we conducted was to test the loss rate to verify the DACK mechanism in the V-MAC system. We sent string data and the three consumers simultaneously sent out Interest packets. When the producer received the Interest packet, it sent out a Data packet. We repeated this process 50,000 times per round, with each transmission consisting of 1024B of data, and a new round began after a 30-second interval. We recorded the frame numbers to calculate the loss rate. The second experiment was a rate test, where we recorded the time to calculate the transmission rate. Finally, we conducted an experiment on the transmission of video streams to observe the final receiving results. We took the average of five experimental results each time, and for the video stream transmission experiment, our comparison object was ad-hoc broadcast transmission.

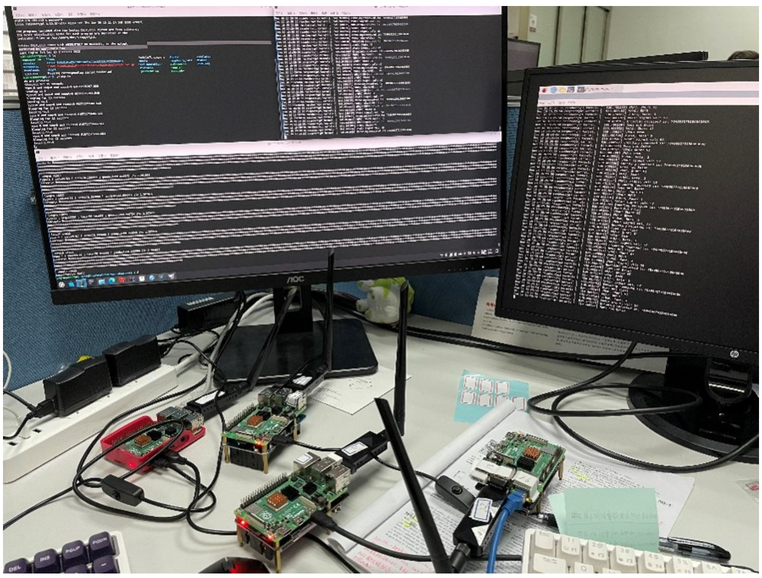
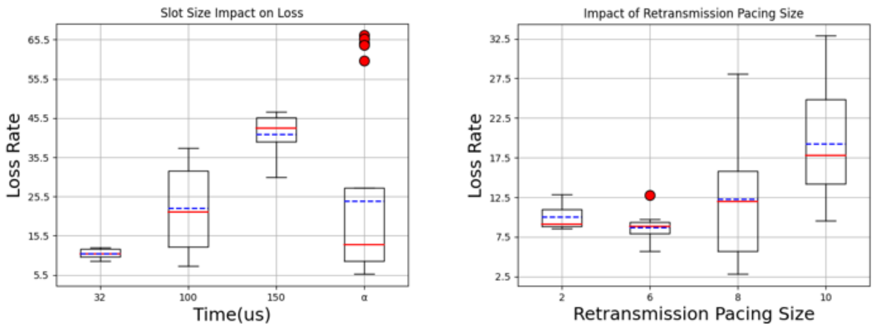


Figure 3: One Consumer and Three Producer

5 Results and analysis

5.1 Loss Rate

Figure 4(a) shows the impact of Slot Size on the system loss rate, and Figure 4(b) shows the impact of Retransmission Pacing Size on the system loss rate. We can see that as long as the parameters are set correctly, the loss rate is relatively low. The optimal parameters in the paper are α for Slot Size and 6 for Retransmission Pacing Size. At the same time, we also observed that the loss rate was not as low as in the original paper's experiments, which is likely due to our experimental environment being in a relatively closed environment with a lot of 2.4GHz interference around. Although the V-MAC system can coexist with normal WiFi frames, its anti-interference ability is not strong, which creates additional processing burden and leads to an increase in the loss rate.



(a) Slot Size (b) Retransmission Pacing Size

Figure 4: Loss Rate with Different Parameters

5.2 Transmission Performance

We can see a clear comparison between V-MAC and ad-hoc broadcast from Figure 5. The reason for using broadcast as a comparison instead of one-to-one communication is that V-MAC's transmission method is currently also in broadcast form, so they are at the same level of comparison. Under ad-hoc mode, the transmission rate has been consistently low and constant, while V-MAC's speed fluctuates greatly, but overall the transmission speed is above 1MB per second. Although this is lower than the maximum speed of 54Mb per second mentioned in the original paper, considering our complex experimental environment, this is a good experimental result.

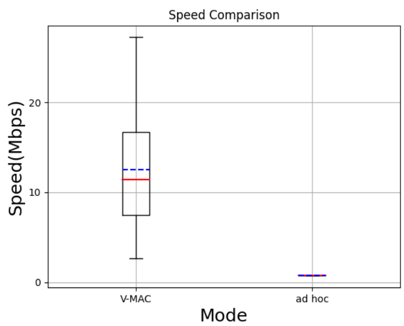


Figure 5: Speed Performance Comparison

5.3 Stream video

The Figure 6 shows the difference between V-MAC and ad-hoc broadcasting in streaming video. Compared to the above rate test, this test is more clear and visible. V-MAC's lowest loss rate can be reduced to 2 percent, which keeps most frames of the video and plays normally. While ad-hoc is even difficult to play sequentially, with most of the time being black screen, it validates the advantage of V-MAC again.

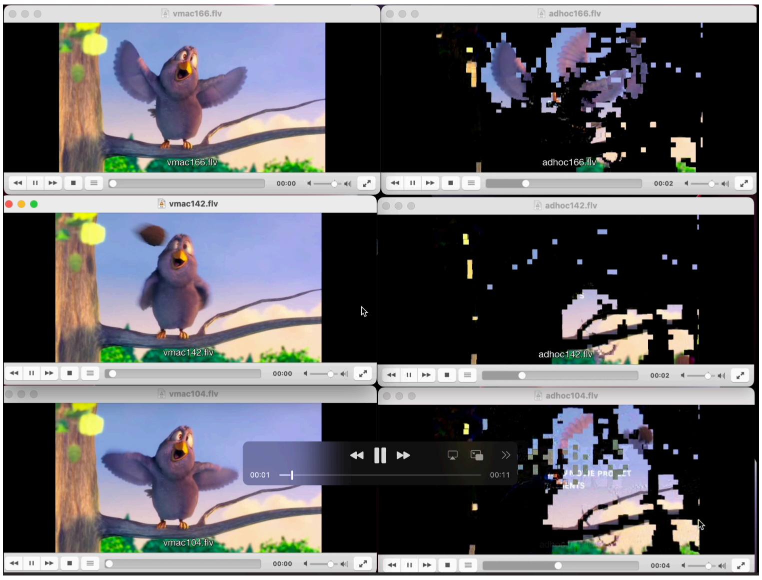


Figure 6: Brocasting in Streaming Video Comparison∂

6 Conclusion and future work

Through the replication of this paper, we have learned about the efficient transmission of V-MAC in broadcast scenarios, as well as the ICN ideas behind its system implementation. In this replication, we tested the performance of the original V-MAC system on our own hardware and environment, and attempted an implementation of an ICN protocol layer. Although we did not benchmark the ICN protocol layer in this experiment, we will continue this work in the future to connect V-MAC with normal applications. Finally, I would like to thank my supervisor, Prof. Lei Zhang, for his valuable guidance and motivation in completing this experiment, as well as my graduate supervisor, Dr. Yaodong Huang, and my classmate. Thank you all!

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