A Survey about the Work of the Coding for Efficient Network Communications Research Group (NWCRG)

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Abstract—**There has been a lot of research on improving transmission quality in networks. One approach is coding on nodes within the network (NC). This can make transmission more secure, reliable, and quick. A group of scientists, in this field, formed in 2013 to gather knowledge and identify open research questions about NC. This paper surveys the content of their finished work and puts it in context with other literature. We concluded that NWCRG fulfilled their goals by examining multiple different topics in NC, showing research challenges, and furthermore solving one challenge themselves.**

Index Terms—**nwcrg, network coding, satellite communication, congestion control, forward erasure correction, content-centric networking, named data networking**

1. Introduction

Encoding and decoding packets not only at the ends of a transmission but also at intermediate nodes of a network, is the central idea of Network Coding (NC) [1]. Network coding can enhance performance in terms of quality (Sections 2.2, 2.3), quantity (Section 2.2), and security [2]. Fragouli and Soljanin decscribe one typical instance of NC [3]: An intermediate node, receiving two bit flows, can halve the payload by bitwise applying the XOR-operator to these two flows. Then the combination is forwarded as one flow instead of two flows to the next node of the network. The receiver gets sufficient knowledge from other components in the network, to calculate the original data of the two flows. This can be done in multiple ways. One is elaborated in the Subsection Two-Way Relay Channel Mode of Section 2.2.

This paper gives an insight into NC by surveying documents of the *Coding for efficient NetWork Communications Research Group* (NWCRG) and putting them in context with related literature. NWCRG published four RFC documents to fulfill their goals of standardizing NC communication, gathering knowledge about NC applications in practice [2], and encouraging researchers to tackle unsolved challenges. These RFCs cover different topics, give an insight into NC, and are summarized in this paper. A detailed survey like this has not yet been conducted and published, while the results of NWCRG have been cited multiple times ([4], [5], [6]) and an overview of NWCRG as a group has been given [7].

The structure of the paper is as follows: In Section 2 the RFCs and related work RFC are examined. Subsection 2.1 gives an overview of definitions and taxonomies gathered by NWCRG. This is followed, in Subsection 2.2, by detailed suggestions to implement NC in satellite communication systems. Different possible uses of congestion control along with forward erasure correction code, a specific NC code, are described in Subsection 2.3. The last RFC, in Subsection 2.4, deals with NC for information centric networking. Section 3 concludes the paper.

2. Work by NWCRG

NWCRG finished and published four RFCs [8]. These are summarized in the following sections. The focus of the summary lies on analyzing the main concepts for RFC 8975, RFC 9265 and RFC 9273. For RFC 8406, an overview of the structure of the document is given because it mostly contains brief definitions which are summaries themselves.

2.1. Terminologies and Taxonomies in NC (RFC 8406)

Overview. The document RFC 8406 [9] by Adamson et al. gives an overview of terminologies and taxonomies in NC, focusing “on packet transmissions and losses” [9] in non-physical layers. RFC 6726 [10], RFC 6363 [11], RFC 5052 [12], RFC 5740 [13], and RFC 5775 [14] were the main sources for the definitions.

First, “General Definitions and Concepts” [9] are introduced, serving as a detailed glossary for the document. Seventeen key terms and their synonyms (or in some cases words to differentiate from) are introduced by describing them. They can roughly be summarized as terms about erasure, coding, symbols, payloads, packets, nodes, and flows.

Second, a “Taxonomy of Code Uses” [9] is described by differentiating between Source and Channel Coding, Intra- and Inter-Flow Coding, as well as Single- and Multi-Path Coding.

Third, a sketch of different, partially matchable coding types is conducted: Linear Coding along with its variations Random Linear Coding and Adaptive Linear Coding combine input data and coefficients. Block Coding and (Fixed/ Elastic) Sliding Window Coding are mutual alternatives for handling data flows. In Systematic Coding, source data is part of the encoded data. Rateless Coding can produce an unlimited number of different codes of the same source data.

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Fourth, basic coding terms are enumerated and defined. Among others, names of different sets of data and their sizes are explained (e.g. Decoding Window, Payload Set). In addition, relevant terms in the context of Linear Codes are mentioned (e.g. Coding Coefficient, Finite Field).

To code in practice, requirements are defined by schemes, needed for a correct coded data transfer. For example, the *Forward Erasure Correction* (FEC) Scheme specifies a distinct FEC code and protocol. FEC describes a type of code, only used in channels that will drop a data packet if it has flaws. In this scheme, it is sent with a protocol, which carries decoding information. One part of the protocol [15], the FEC Payload ID, is described further in the document. It serves as an identifier for segments of a packet which are used in the coding process.

Related Work. Terms and important concepts are generally explained in works about NC ([16], [17]) , but there has not been a document with this focus before RFC 8406, that is widely available. Its content has been reused in the field of NC, mainly by NWCRG members ([16], [18], [19]) but also by others. For instance, Zverev et al. defined some terms based on the RFC 8406, for their work about robust QUIC, a low latency transport protocol [4].

2.2. NC for Satellite Systems (RFC 8975)

The objective of RFC 8975 [19] is, to show opportunities to integrate NC techniques in *SATellite-COMmunication* (SATCOM) networks.

One use case of a SATCOM network is the communication of two devices on the ground over a satellite in space. As the devices can communicate with a satellite, they are called (satellite) terminals. If a direct transfer of data from one terminal to the other is not possible, the sender first transmits the data to the satellite, which forwards it further to the receiver. The transmission usually requires arranging the data in multiple packets, which are sent individually.

In a SATCOM process, NC can be used to reduce the amount of sent packets, decrease the occurrence of mistakes in the transmission and support a quicker recognition along with re-submission of lost packets, while not diminishing the amount of transferred data content.

Two-Way Relay Channel Mode. Using NC, it is possible to reduce the number of packets sent, in a Two-Way Relay Channel Mode. For the continuous communication of two terminals with each other, each terminal transmits a data flow to a satellite. Instead of forwarding the original messages to the receiving terminals, the satellite combines the two data flows. This one flow is then sent. It is received by both terminals as illustrated in Figure 1. By knowing what they sent before, they can decode the data and read the message of the other terminal. This is how, by not sending two data flows but one which carries data for both terminals (multicasting), the amount of data is reduced.

Reliable Multicast. Multicast provides an opportunity to recover lost data, using NC: Packets in a multicast flow are sent from one satellite to multiple terminals. If a packet gets lost at a terminal, the terminal sends a negative acknowledgment back. A repair packet is then encoded in the multicast flow, in a way that that the addition of the repair data does not require sending additional packets. Using this packet, the terminal restores the data. This kind of Reliable Multicast can be used in multicasts or broadcasts described in "Secure Hybrid In Network caching Environment" by the European Space Agency [20], in NACK-oriented reliable multicasts and in file delivery over unidirectional transport [21].

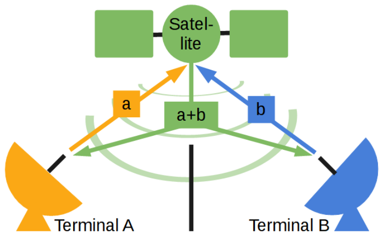

Figure 1: Two terminals communicating in a Two-Way Relay Channel Mode

Hybrid Access. NC application can be used to deal with packet losses in multiple-path communications like Hybrid Access. Using it can also lead to higher flexibility towards the order of packets. NC is applied at the transport layer, more precisely at the at any end user equipment and/ or the concentrator. The concentrator serves as the interface which aggregates multiple channels to the server. This approach has been implemented and published in an ETSI Technical Report [22].

End-to-End Encryption. Packet losses are usually prevented by a *Performance Enhancing Proxy* (PEP) server in a LAN to satellite transmission but User Datagram Protocol based end-to-end encryption makes PEP unusable. Therefore, losses would occur in an end-to-end encrypted wireless LAN SATCOM system. Network Coding may be applied at multiple points during the transmission process – at the end user, satellite gateway, access gateway, or network function. The usage may result in a reduction in packet loss.

Other Packet losses. Sub-second varying physical channel conditions will not necessarily be corrected on the physical layer in time. Consequently, packets get lost. However, they may be recovered through NC mechanisms in other layers.

Another cause of packet losses may be gateway handovers. Reasons for that loss, for instance, flaws in synchronization or trigger-algorithms, can be reduced by using NC.

Research Challenges. In the process of writing the document, the following open research topics were identified (read [19] for more details): Combining NC and Congestion Control, which is used in most SATCOM Systems. Balancing the trade off between benefits of redundant information to recover mistakes and adding too much redundancy in the context of quickly varying channel conditions. Several topics about the implementation of NC in Virtual Network functions. The deployment of Delay/Disruption-Tolerant Networking.

Related Work. Even though there has been little commercial application, a lot of research about NC in SATCOM systems has been done. Cloud et al. encountered challenges when implementing NC in a SATCOM system [23]. Ghanem et al. described two “Channel Virtualization Schemes for Satellite Multicast Communications” [17]. Some of the research cited the RFC 8975 or its draft: Chiti et al. focus on NC applied in SATCOM for reliable multicasts [24]. Thomas et al. reference the RFC 8975 for a description of a generic SATCOM architecture in an article about Google QUIC [5].

2.3. Forward Erasure Correction Coding and Congestion Control in Transport (RFC 9265)

RFC 9265 [25] elaborates different possible relations of *Forward Erasure Correction* (FEC) and transport layer *Congestion Control* (CC). FEC is implemented through NC, processing and changing packets on intermediate nodes of a network. The goal of the FEC code, introduced in Section 2.1, is restoring lost packages at the end of a transmission. The encoding process results in so-called symbols. Specifically, source symbols which contain the source data and repair symbols which contain repair information for one or more source packets. The number of repair symbols is usually decided by a certain rate in comparison to the number of source symbol or by a fixed number. These symbols get reassembled in network packets, which are transmitted. When decoding, the information of the repair symbols is used to restore source symbols that got lost in transmission. A repair symbol can contain the data for exactly one source symbol or a combination of source data. E.g., storing in one repair symbol the XOR combination of multiple source symbols, the repair symbol can restore one source symbol, if exactly one source symbol got lost.

If reliability is not needed, FEC is usually implemented as an alternative to mechanisms for reliable transfer like the retransmissions of lost packages. Because it is possible that a source symbol and its repair symbol get lost, it is used for partially reliable or unreliable data transfers. An example for a fitting protocol is QUIC with the unreliable datagram extension [26]. In special cases a reliable transfer with FEC is also possible (details in [25]).

FEC can be applied right before, within, or after the control entities of the transport layer, as illustrated in Figure 2. This position of FEC determines the possibilities to communicate with CC of the transport. Congestion Control is a mechanism of the sender and the receiver, which calculates if the path is congested and adjusts a congestion window accordingly. By the size of the congestion window, the sender then knows how many packets it can send without losing data by congestion.

FEC above the transport layer. With FEC applied above the transport, the data is FEC encoded before CC and FEC decoded after CC as shown in Figure 2 in green.

CC gets network packets, on which it calculates the congestion. It does not matter if these network packets contain repair or source symbols. Hence, CC can work as it would without FEC and has the same control over the congestion as it would have without.

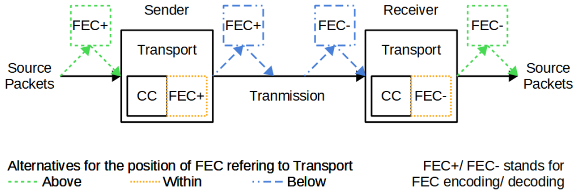

Figure 2: Overview FEC and CC

The core advantage of using FEC at this position lies in the fact that CC can be implemented without special considerations. This might not be the case for FEC within or below the transport, as will be explained.

FEC within the transport layer. The application of FEC within the transport, allows a joint control of CC and FEC. The source packets get encoded by the same controller that decides at what time packets are sent to the receiver. At the receiver a joint controller operates FEC and CC. It can indicate congestion and the use of repair packets to recover source symbols to the sender.

Therefore, it is a flexible solution. The sender controller knows about congestion as well as the number of lost packets and consequently can adjust the number of repair packets to the system’s needs.

Should the focus of the system be latency performance, repair packets only get send if no congestion is induced by the additional data.

If there is a lot of data traffic in relation to the transmission capacity and some packets get lost, blocking a fixed percentage of the transmission capacity for repair packets might be useful. A separate CC mechanism can then be implemented for repair symbols, which can be send independent of the source symbol congestion.

The system may dynamically adjust to its current needs by balancing higher congestion and the number of repair packets used in relation to the ones sent. If in relation many repair packets get used, it is likely that the channel is unreliable and transmits a smaller share of packets correctly. To lose as little data as possible more repair packets might be sent, accepting a lower transmission rate. And the other way around if high congestion occurs, the number of repair packets might be reduced, accepting more lost source packets.

A drawback of FEC within transport is that the fitting solutions for the system might require a complex implementation.

FEC below the transport layer. Figure 2illustrates the position of FEC below the transport in blue. Encoding happens after the transport layer forwards data but before the link layer processes it. Communication between FEC and CC is not planned.

This position of FEC is generally beneficial if numerous packets get lost in a transmission. The repair symbols then are employed and lead to a better transmission performance.

The RFC covers only the scenario of the transport controllers not knowing about FEC. FEC sends its repair symbols on top of the original data and restores original packets before they reach the transport receiver, which does congestion control. The receiver misunderstands restored packets which were lost, as sent correctly. Therefore, normal loss-based congestion detection does not work correctly. For instance, a CC controller miscalculates a congested path as good because of FEC repairs the data in time. Using existing signals to indicate a restoration, might be a possibility to still use loss-based congestion. In contrast, delay-based congestion detection works fine. The delay of source packets, which is induced by congestion by source symbols and repair symbols, shows the controller, that a reduction of packets is necessary. This stops congestion from building up. Problems may still occur if, due to external circumstances, congestion generally cannot be prevented. In this case, sending a fixed amount of repair symbols at a fixed rate and applying a separate congestion control entity for repair symbols, might enhance a transmission.

Related Work. Most research in this area investigates which joint dynamic control of CC and FEC is best for a specific system. The following works are examples for this: Tsugawa et al. proposed a general Adaptive FEC Code Control for TCP video streaming in 2007 [27]. In 2017 TCP-TFEC, a method to improve the throughput in wireless LAN, in comparison to Tsugawa's work, was suggested by Teshima et al. [28]. Sharma et al. published work about a multi-path loss-tolerant transport protocol, using CC and FEC [29].

Furthermore, there has been research in NC that has buildt on the RFC 9265, for instance Wu et al. cited RFC 9265 as a reference for complex implementations of FEC and CC in the Transport layer, in their article on A Survey on Multipath Transport Protocols Towards 5G Access Traffic Steering, Switching and Splitting [6].

2.4. NC for Information-Centric Networking (RFC 9273)

RFC 9273 [18] shows the current state of research in NC for *Information-Centric Networking* (ICN), particularly Content-Centric Networking and Named data Networking, by explaining main concepts, technical considerations, and potential challenges.

Process. An ICN can simplified be described as multiple consumers (e.g. end user) connected by multiple forwarders to multiple producers (e.g. server). To receive data, a consumer must create an interest packet, which describes what data it is interested in. Then it sends the interest packet to a so-called forwarder, a node in the network. The forwarder first checks if his cache, also called content storage, contains the requested data. If successful, it sends the data back. Otherwise, searches for a fitting entry in the *Pending Interest Table* (PIT), if it already contains an entry, the two requests can be aggregated. Otherwise, it inserts a new entry, containing the name of the request along with the requesting interface identification. Then it forwards the request to another fitting interface. If the interface is a forwarder, the same process repeats. In contrast, if the interface is a producer, it prepares the wanted source packets by grouping them into blocks. Each block consists of a fixed number (k) source packets, which are encoded with a coding vector, chosen by the producer. The encoded block which contains k source packets and additional repair packets, is sent to the requester. Following the trail of PIT entries, the data is transported back to the consumer. Forwarders passing the data, can store the data in their content storage and can recode repair packets, if they have sufficient knowledge. The consumer is usually able to decode the data after receiving at least k source or repair packets of a block. It also takes security measures, for instance checking for origin authentication.

Technical considerations. Two important technical considerations, mentioned in the RFC, are backwards compatibility and content naming. ICN network parts with NC should be composable with ICN network parts without NC.

Names of packets and blocks are important, because they could be used for the comparison in the PIT, Content Storage and in interest packets. The system can either follow a naming scheme of unique or non-unique names. Unique naming requires every packet to have a different name but the name includes metadata like the coding vector. Non-unique naming in contrast, allows packets to be called the same, which might make renaming on inner nodes of the network necessary, if a packet name is already used on that node. The metadata is stored in the payload of the packet. Furthermore, different possibilities to decide on the name can be considered. Either the consumer is familiar with the naming conventions and already uses the right name in the interest packet, the producer decides on coding vectors and names when getting a request, or the naming scheme can be looked up by the consumer in a manifest.

Related Work. A lot of research has been conducted about NC in ICN ([30], [31], [32]). Only a few papers cite the RFC or its draft, the reason for this could be that the RFC is very recent, having only published in August 2022. In particular, the paper was named as related work by Borgia at al. in "Reliable Data Deliver in ICN-IoT Environments" [33] and by Malik et al. in "MICN: a network coding protocol for ICN with multiple distinct interest per generation" [34].

3. Conclusion

The implementation of NC in networks leads to benefits in transmission processes. A smaller payload can be received by an analytic aggregation of packets. Lost packets can be recovered by sending additional repair packets. NWCRG shows this among other research results in their papers. Besides, they identified open research challenges. One challenge, described in RFC 8975, was the "Joint Use of Network coding and Congestion Control in SATCOM System", taken on more generally in RFC 9265. Their research ties into lots of other related work as shown for each RFC. Their documents have been cited multiple times, which indicates a relevance of the research done by NWCRG.

References

[1] T. Shang and J. Liu, *Secure Quantum Network Coding Theory*. Springer Singapore, 2020.

[2] "Coding for efficient NetWork Communications Research Group (nwcrg)," https://datatracker.ietf.org/rg/nwcrg/about/, [Online; accessed 24-September-2022].

[3] C. Fragouli and E. Soljanin, "Network coding fundamentals," *Foundations and Trends® in Networking*, vol. 2, no. 1, pp. 1–133, 2007. [Online]. Available: http://dx.doi.org/10.1561/1300000003

[4] M. Zverev, P. Garrido, F. Fernandez, J. Bilbao, O. Alay, S. Ferlin, A. Brunstrom, and R. Aguero, "Robust quic: Integrating practical coding in a low latency transport protocol," *IEEE Access*, vol. 9, p. 138225 – 138244, 2021, cited by: 0; All Open Access, Gold Open Access, Green Open Access. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85117204172&doi=10.1109%2fACCESS.2021.3118112&partnerID=40&md5=1ba7c5b53dab26711f322a854176c53a

[5] L. Thomas, E. Dubois, N. Kuhn, and E. Lochin, "Google quic performance over a public satcom access," *International Journal of Satellite Communications and Networking*, vol. 37, no. 6, pp. 601–611, 2019. [Online]. Available: https://doi-org.eaccess.ub.tum.de/10.1002/sat.1301

[6] H. Wu, S. Ferlin, G. Caso, O. Alay, and A. Brunstrom, "A survey on multipath transport protocols towards 5g access traffic steering, switching and splitting," *IEEE Access*, vol. 9, p. 164417 – 164439, 2021, cited by: 6; All Open Access, Gold Open Access, Green Open Access. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85121352474&doi=10.1109%2fACCESS.2021.3134261&partnerID=40&md5=c29f81b848edb8cbc051c3f8b2fc1208

[7] Toksoy, Aral and Stubbe, Henning and Holzinger, Kilian, "NWCRG Closing Report," in *Proceedings of the Seminar Innovative Internet Technologies and Mobile Communications (IITM)*, 2022.

[8] "Coding for efficient NetWork Communications Research Group (nwcrg)," https://datatracker.ietf.org/rg/nwcrg/documents/, [Online; accessed 24-September-2022].

[9] B. Adamson, C. Adjih, J. Bilbao, V. Firoiu, F. Fitzek, S. Ghanem, E. Lochin, A. Masucci, M. Pedersen, G. Peralta, P. Saxena, and S. Sivakumar, "Taxonomy of coding techniques for efficient network communications," *RFC*, vol. 8406, 6 2018.

[10] T. Paila, R. Walsh, M. Luby, V. Roca, and R. Lehtonen, "Flute - file delivery over unidirectional transport," *RFC*, vol. 6726, 11 2012.

[11] M. Watson, A. Begen, and V. Roca, "Forward error correction (fec) framework," 10 2011.

[12] M. Watson, M. Luby, and L. Vicisano, "Forward error correction (fec) building block," *RFC*, vol. 5052, 8 2007.

[13] B. Adamson, C. Bormann, M. Handley, and J. Macker, "Nack-oriented reliable multicast (norm) transport protocol," *RFC*, vol. 5740, 11 2009.

[14] M. Luby, M. Watson, and L. Vicisano, "Asynchronous layered coding (alc) protocol instantiation," *RFC*, vol. 5775, 4 2010.

[15] M. Luby, L. Vicisano, J. Gemmell, L. Rizzo, M. Handley, and J. Crowcroft, "Forward error correction (fec) building block," *RFC*, vol. 3452, 12 2002.

[16] V. Roca and B. Teibi, "Sliding window random linear code (rlc) forward erasure correction (fec) schemes for fecframe," *RFC*, vol. 8681, 1 2020.

[17] S. A. M. Ghanem, A. E. Gharsellaoui, D. Tarchi, and A. Vanelli-Coralli, "Network coding channel virtualization schemes for satellite multicast communications," *CoRR*, vol. abs/1704.04790, 2017. [Online]. Available: http://arxiv.org/abs/1704.04790

[18] K. Matsuzono, H. Asaeda, and C. Westphal, "Network coding for content-centric networking / named data networking: Considerations and challenges," *RFC*, vol. 9273, 8 2022.

[19] N. Kuhn, E. Ed, and E. Lochin, "Network coding for satellite systems," *RFC*, vol. 8975, 1 2021.

[20] S. P. Romano, C. Roseti, and A. Tulino, "Shine: Secure hybrid in network caching environment," 06 2018, pp. 1–6.

[21] B. Adamson, C. Bormann, M. Handley, and J. Macker, "Nack-oriented reliable multicast (norm) transport protocol," *RFC*, vol. 5740, 11 2009.

[22] "Multi-link routing scheme in hybrid access network with heterogeneous links," *ETSI TR*, vol. 103, pp. 351–V351, 7 2017.

[23] J. Cloud and M. Médard, "Network coding over SATCOM: lessons learned," *CoRR*, vol. abs/1506.06154, 2015. [Online]. Available: http://arxiv.org/abs/1506.06154

[24] F. Chiti, R. Fantacci, and L. Pierucci, "Energy efficient communications for reliable iot multicast 5g/satellite services," *Future Internet*, vol. 11, no. 8, 2019. [Online]. Available: https://www.mdpi.com/1999-5903/11/8/164

[25] N. Kuhn, E. Lochin, F. Michel, and M. Welzl, "Forward erasure correction (fec) coding and congestion control in transport," *RFC*, vol. 9265, 7 2022.

[26] T. Pauly, E. Kinnear, and D. Schinazi, "An unreliable datagram extension to quic," 3 2022.

[27] T. Tsugawa, N. Fujita, T. Hama, H. Shimonishi, and T. Murase, "Tcp-afec: An adaptive fec code control for end-to-end bandwidth guarantee," in *Packet Video 2007*, 2007, pp. 294–301.

[28] F. TESHIMA, H. OBATA, R. HAMAMOTO, and K. ISHIDA, "Tcp-tfec: Tcp congestion control based on redundancy setting method for fec over wireless lan," *IEICE Transactions on Information and Systems*, vol. E100.D, no. 12, pp. 2818–2827, 2017.

[29] V. Sharma, K. Kar, K. Ramakrishnan, and S. Kalyanaraman, "A transport protocol to exploit multipath diversity in wireless networks," *IEEE/ACM Transactions on Networking*, vol. 20, no. 4, p. 1024 – 1039, 2012, cited by: 45. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84865319305&doi=10.1109%2fTNET.2011.2181979&partnerID=40&md5=6bce9cc31d720be9836c2fc7bb065b41

[30] J. Zhang, L. Ma, Z. Cai, and X. Wang, "Network coding-based multipath content transmission mechanism in content centric networking," in *2017 IEEE 9th International Conference on Communication Software and Networks (ICCSN)*, 2017, pp. 1012–1015.

[31] R. Boussaha, Y. Challal, and A. Bouabdallah, "Single-path network coding authentication for software-defined named data networking," in *2019 IEEE/ACS 16th International Conference on Computer Systems and Applications (AICCSA)*, 2019, p. 17.

[32] ——, "Authenticated network coding for software-defined named data networking," vol. 2018-May, 2018, Conference paper, p. 1115 – 1122, cited by: 3. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85052294658&doi=10.1109%2fAINA.2018.00160&partnerID=40&md5=8e21bdabfeaa8d50e9d0d89dd60587bb

[33] E. Borgia, R. Bruno, and A. Passarella, "Reliable data delivery in icn-iot environments," *Future Generation Computer Systems*, vol. 134, p. 271 – 286, 2022, cited by: 0; All Open Access, Green Open Access. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129691482&doi=10.1016%2fj.future.2022.04.004&partnerID=40&md5=fad6f5c4b8e6289bf10921f5fdf0316b

[34] H. Malik, C. Adjih, C. Weidmann, and M. Kieffer, "Micn: A network coding protocol for icn with multiple distinct interests per generation," *Computer Networks*, vol. 187, 2021, cited by: 0; All Open Access, Bronze Open Access, Green Open Access. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85099513258&doi=10.1016%2fj.comnet.2021.107816&partnerID=40&md5=886e64b2f73b5c7a1f36f050fe411d60