Implementation of Lossy Forwarding and Joint Decoding for Wireless Ad Hoc Networks

Keshav Goyal

***Abstract*—Modern wireless networks require reliable, faster and power efficient transmission capabilities. This is being achieved through cooperative-communication which potentially exploits every network node as a relay, thus reducing load and reliance on any specific node. In this article we discuss "lossy forwarding and joint decoding (LF-JD)" as a method of cooperative-communication [1]. LF-JD scheme has proven to have a high bit-rate and a lower transmission power as the penetration distance reduces with the introduction of multi-hop relays. This article proposes changes to current physical and network layer protocols that would help implement LF-JD. This implementation is then used to compare the LF-JD scheme to the current protocols in terms of throughput, delays and packet qualities.**

***Index Terms*—LF ("Lossy Forwarding"), JD ("Joint Decoding"), CBF ("Contention-based Forwarding"), CSMA/CA, IEEE 802.11, (LLR) "Likelihood Function", MAC, LF-MAC, LF-CBF, ARQ ("Automatic Repeat Request"), Multi-hop Forwarding, DTC ("Distributed Turbo Coding")**

I. Introduction

Let us consider the crowd in a stadium during an important football match. The capacity of a big stadium would be about 60,000 seats. Suppose each of these 60,000 fans wants to stream the score of another football match on their mobile phones using the wireless network in the stadium. Such a situation is bound to be overwhelming for a conventional wireless network unless there are a huge number of network base stations. This problem motivates us to introduce the concept of cooperative communication which would potentially convert each mobile phone into a relay node, thus reducing the number of network stations required [2]. This method is much more efficient in terms of power and cost while also reducing the outage probability as compared to a conventional wireless ad hoc network.

Now, if we consider the example of autonomous vehicles communicating with each other on the road, we have an ever-changing network topology at our hands. Although this example would employ cooperative network protocols, we are faced with the following problems:

- The dynamic network topology may lead to lossy radio links.
- Re-transmissions in the case of erroneous messages may not be feasible.
- Conventional cooperative schemes which involve stop-and-wait protocols at every relay prove to be too slow to avoid collisions and split second decisions.

The authors are with International Institute of Information Technology Bangalore, India. email: {mailidfirstauthor, mailidsecondauthor, mailidthirdauthor}@iiitb.org.

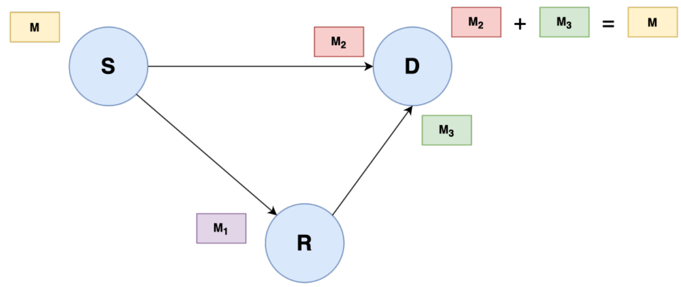

Fig. 1: A basic Wireless Network of three nodes namely S (Source), R (Relay) and D (Destination) [1]

Thus, the need arises for faster forwarding techniques while still retaining the quality of the decoded message at the destination with respect to the source. The concept of lossy forwarding (LF) [3] is able to tackle the issues of quickness and lossy links. In this scheme relays do not perform any integrity checks on the data and forward the data irrespective of its quality. This leads to erroneous information reaching the destination, defeating the whole purpose of the network. The concept of joint decoding (JD) takes care of the quality of packets by applying distributed turbo coding (DTC) [4] and log-likelihood functions [5] over multiple erroneous copies of the same message. Thus, when used together, LF-JD mechanism enables fast and reliable communications.

In this article, we have used a very simple topology for cooperative communication involving a source, a destination and a single relay where all the three links involved are lossy (Fig. 1). The message M from S is received in erroneous forms as M_1 and M_2 at R and D respectively. Relay R then decodes M_1 and forwards it to D without any quality checks. D receives M_3 from R and M_2 from S, it then carries out JD over M_2 and M_3 in order to determine the original message M.

LF-JD mechanism has proven to have a high spectral efficiency (high bit-rate), low outage probability and lower transmission power requirements as compared to other cooperative communication methods [3] [4] [6]. In this article we propose changes to the existing MAC protocol and the contention-based forwarding algorithm [7] in order to implement LF-JD mechanism. Then we further compare the LF-JD protocols to the existing methods through simulations.

II. System Model

The LF-JD method reduces errors and improves bit-rate by enabling errors in individual transmissions and using DTC. The destination receives multiple messages which although

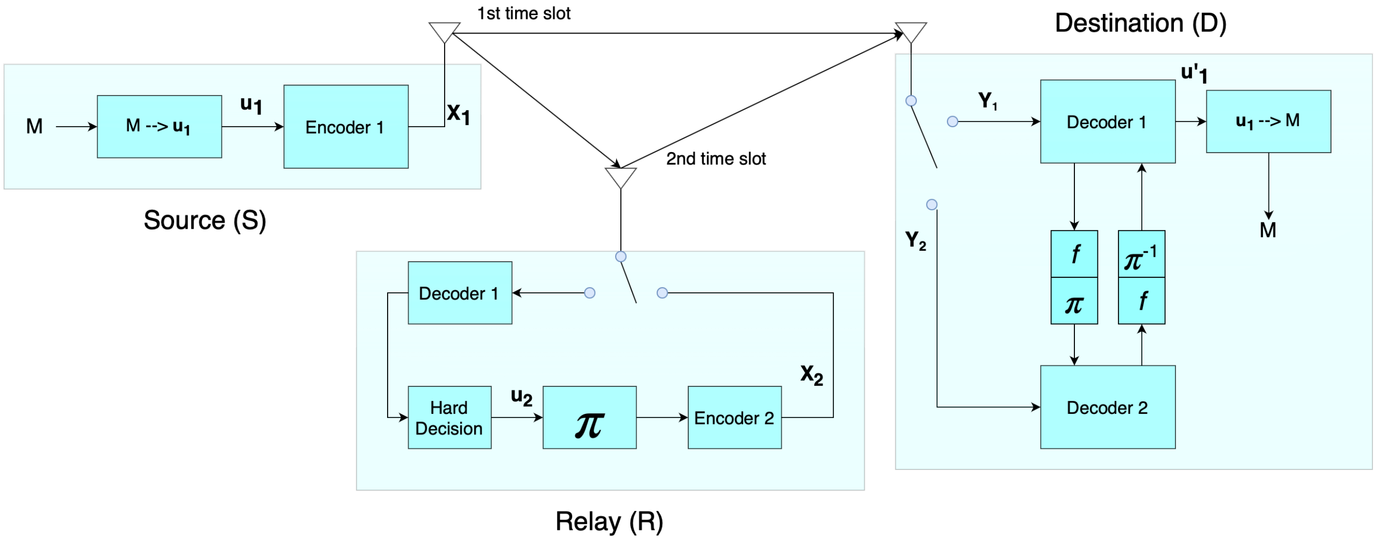

Fig. 2: A detailed diagram of our basic model, π^{-1} and π represent the disinter-leaver and inter-leaver used in DTC respectively. f represents the "log-likelihood function" [1]

erroneous are still correlated and this correlation can be used to retrieve the original message using joint-decoding. Thus even though the quality of a single message is poor, the combined decoded message is still intact.

The detailed diagram for the simple topology can be seen in Fig. 2. S forwards X_1 which is encoded form of u_1 to R and D during the first slot. R decodes this message taking it as binary input, and then re-encodes the message after carrying out two checks on the message as explained in further sections. It then forwards the encoded message X_2 to D. D receives the messages as Y_1 and Y_2 from S and R respectively. Y_1 is passed to decoder-1 while Y_2 is passed to decoder-2. To carry out joint-decoding, D needs to know the reliability of the link between S and R. This information is passed to D from R as bit error probability. The bit error probability is used to predict the influence of messages Y_1 and Y_2 on the original message. The two decoders at D exchange information and decide on the original message using log-likelihood ratios (LLR). "The log-likelihood function is used to predict the probabilities of the influence of certain unknown parameters on a sample scenario" [5]. In our case the unknown parameters can be considered to be the actual message and the samples are the erroneous messages received at the destination.The destination aims to obtain the original message u_1 as a result of joint-decoding mechanism. Thus, LF-JD provides the following advantages in a cooperative communication network:

- **Disjoint paths:** The destination receives multiple messages from disjoint routes which increases the probability of non-erroneous communication.
- **Efficient use of received signal energy:** This is achieved through two factors, first, the message is received by multiple relay nodes. And second, even the relays which receive erroneous packets broadcast information which increases the use of received signal energy.
- **No need for re-transmission:** The relays act as FEC (Forward Error Correction) which does not need any re-transmissions to correct errors. This is achieved as the destination uses joint-decoding to establish a relation between the multiple copies received. It then retrieves the original message from the multiple copies as it knows that the copies are related to the actual information sent from source.

III. Proposed design

A. *Lossy Forwarding MAC (LF-MAC)*

Now, we have already seen that to implement LF-JD we need protocols that can control channel access in order to avoid collisions of links from multiple relays. We also need a method to give uniqueness to each erroneous instance of the same message. This is done through a proposed variant of CSMA/CA protocol, called LF-MAC. All frames are considered broadcast frames. The networks layer of every node decides whether it is a relay node according to two criteria:

- The error quality of the packet and whether the metadata of the packet is preserved or not.
- The location of the potentially relay node with respect to surrounding nodes. This affects the lossy nature of the path through current node.

The LF-MAC protocol proposes a new data-flow, frame-format, channel-access mechanism and reliability protocol.

1) Data Flow: Fig. 3 illustrates the data flow incorporated in LF-MAC. Each message is given error-less metadata which specifies its source, sender and destination. This metadata is contained in the PHY header of 31 $bytes^2$. Every relay conducts two message checks once a received message is decoded, first, it is checked if the metadata has been preserved. And second, the bit-error rate of the message is evaluated, if this is greater than certain threshold then the message is dropped [1]. Otherwise, the network layer decides whether the node should act as a relay based on the routing protocol discussed in further sections. At the destination the same two

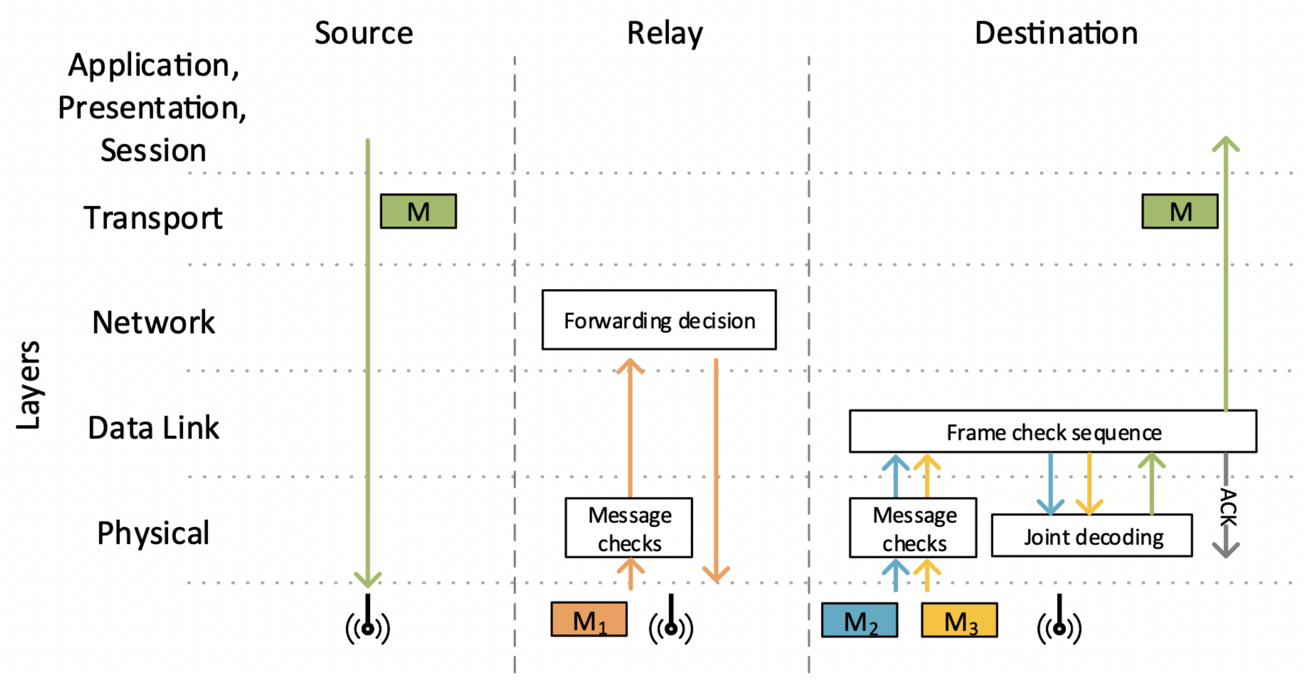

Fig. 3: Data-flow for LF-MAC [1]

checks are conducted. In addition to that, destination also checks the end-to-end quality of the message. This is done using the Frame Check Sequence of the message copy. If the current copy fails the test then it is stored as M_1 and the destination waits for M_3 to be received. When M_3 also the fails the test the Joint Decoding algorithm is initiated. This then gives a message M as the result. The end-to-end check is carried out on message M too. If it fails then the destination again waits for another message copy to be received and stores the message M. This process ends once a good quality message is obtained or else when the timer runs out in which case the information is dropped. The correct message is sent to the upper layers at the destination and an ACK is received to be broadcast back to the source. This ACK is very small and consists only the unique metadata of the message copy in the PHY header.

2) Frame-Format: The header format for LF-MAC can be seen in Fig. 4. The PHY header of each packet consists of the three MAC addresses of source, sender and destination. The contents of the header never change during the communication. The header contains an indicator field and a sequence field. The indicator field contains the bit error probability which signifies the quality of the corresponding packet. The sequence field is used to uniquely identify consecutive messages. The header also contains an inter-leaver index field and a checksum field which is used to check the correctness of the header [8]. Whereas, the ACK only has the source, sender and destination as the contents of the PHY header because it is supposed to be small in size.

3) Channel-Access Algorithm: This procedure is similar to IEEE 802.11. It works on the principle, "listen first and then speak". The source waits for the channel to be vacant for LIFS (long inter-frame space period) [9] and then it sends the packet after some back-off slots [1]. This is similar to CSMA/CA procedure. The relay too sends the data after some back-off slots in order to avoid collisions. Once the destination is satisfied with the quality of received message, it sends the ACK after waiting for "short inter-frame space period (SIFS)" [9].Thus, It is the time required by the destination node in between receiving a satisfying result from JD and answering with an ACK.

4) Reliability Protocol: For the basic topology a stop-and-wait "ARQ (automatic repeat request)" is used [10]. The source has a predefined waiting time for the ACK, after which the next packet is sent. The ACK is sent after SIFS from the destination. Relays forward the ACK on priority to avoid any collisions [8].

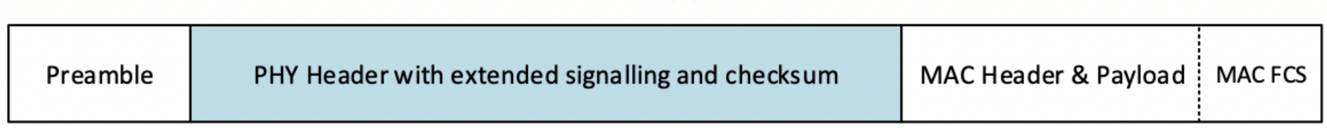

Fig. 4: PHY header modified for LF-MAC (blue shaded part) [1]

B. Routing Protocol for LF-JD

A Routing protocol may not be of much significance in the basic ad hoc network of three nodes. But, in practical situations such as the example of a stadium full of people or vehicles on the road, need arises to incorporate forwarding algorithms in order to manage multi-hop relays. This is achieved through a proposed routing algorithm that is based on the CBF algorithm [7]. CBF uses the relative position of every node in the ad hoc network. In this technique every node takes a decision whether to act as a relay or not. If the node acts as a relay then it broadcasts the message to every neighbour and they further take the decision whether to drop the information or to relay it. This decision is taken in a very intelligent manner. The potential relay node starts a timer during which it stores the message copy. The duration of this timer depends on the relative positioning of the node with respect to the source and destination. Better the position in terms of link quality, lesser is the timer duration. If the node receives another copy of the message during this duration, it means that there exists a better positioned node in the network that can become the relay (because that node had a shorter buffer time and thus is better positioned). In such cases the current node drops the message, otherwise it starts acting as a relay once the timer ends. This is a greedy algorithm variant.

To use CBF with lossy forwarding and joint decoding a few changes are proposed to the existing CBF model. The proposed model is called LF-CBF [11]. The following changes are proposed:

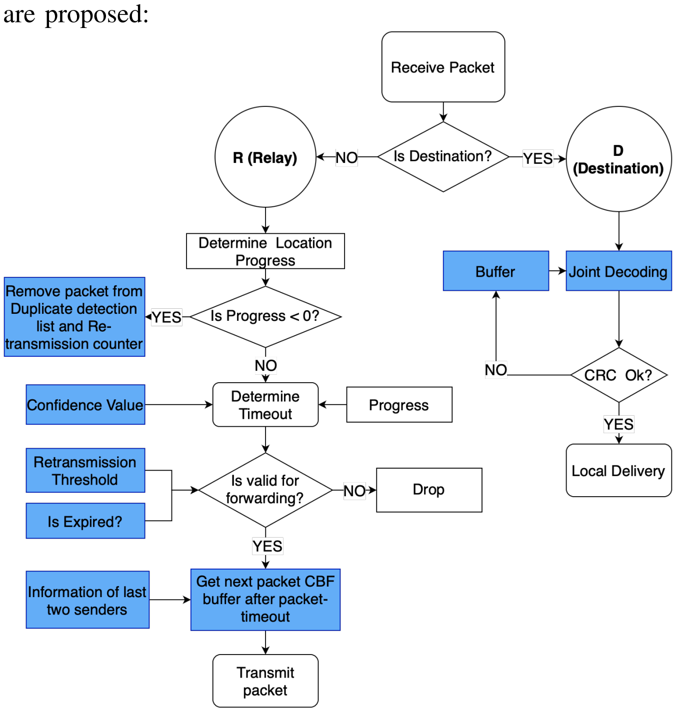

Fig. 5: The flowchart showing LF-CBF algorithm with the blue boxes depicting the changes made to conventional CBF [1]

- **Multiple Relays:** In the CBF algorithm, the destination receives a single message copy as all others are dropped by the relays. This defeats the purpose of lossy forwarding. LF-CBF changes this by introducing a counter that keeps track of the number of duplicates received by the node during the buffer timer. If this counter is less than a certain threshold then the node is allowed to be a relay. This threshold is chosen by taking into account the pattern by which link quality depreciates with worse relative positioning of a node.
- **Determine Buffer Time:** Nodes calculate the buffer time using the "data packet's confidence value provided from the PHY, which estimates the number of errors in the packet" [1]. The packets having higher confidence value will have smaller buffer times.
- **Reduce Unwanted Drops:** If the node receives packets that are below certain threshold of quality, then they are not considered in the counter of duplicate copies. This avoids any drops that should not have occurred.
- **Choose Packets with Unrelated Errors:** The relays select the packet which has the most unrelated errors to be forwarded. This is done so that the destination gets unrelated copies and the JD mechanism is successful in retrieving the original message. The relatedness of a packet is measured by its path. More different the path, more diverse are the errors in the packets. In our basic model only two past nodes are required to define the path.

The changes to CBF are illustrated as a flow-chart in Fig. 5.

IV. Results and Discussion

A. Performance of LF-MAC and MAC

The comparison of LF-MAC with conventional lossless MAC is done in two ways with results shown in Fig. 6(a) and Fig. 6(b) respectively. The comparison table is enlisted in Fig. 7. The first model reduces the quality of the channel from lossless to lossy and compares the throughput of Lossless and LF-MAC. It is observed that for a particular range of quality of the channel the lossless MAC ceases to provide any connectivity at all while LF-MAC still remains connected. In the second model, length of links S-R and S-D are fixed at 300 m while that of the R-D link is increased to make it lossy. This method also observes that the throughput of LF-MAC is higher for all ranges of link quality.

B. Performance of LF-CBF and CBF

The performance evaluation of LF-CBF is carried out based on two factors:

- **Reliability:** The ratio of number of good packets received with respect to the number of packets broadcast by the source (PSR : Packet-success ratio) is used to measure network reliability.
- **Speed:** The time gaps between the transmission and acceptance of all messages are averaged to get the average time taken for communication (E2ED : End to End Delay). This helps in measuring the speed of the network.

For this experiment, an example of 10 vehicles on a single road was considered. Eight vehicles acted as two sets of four parallel relays lying between the source and destination vehicles. The link quality was changed by changing the power of transmission of the vehicles. This topology and corresponding observations have been illustrated in Fig. 8.

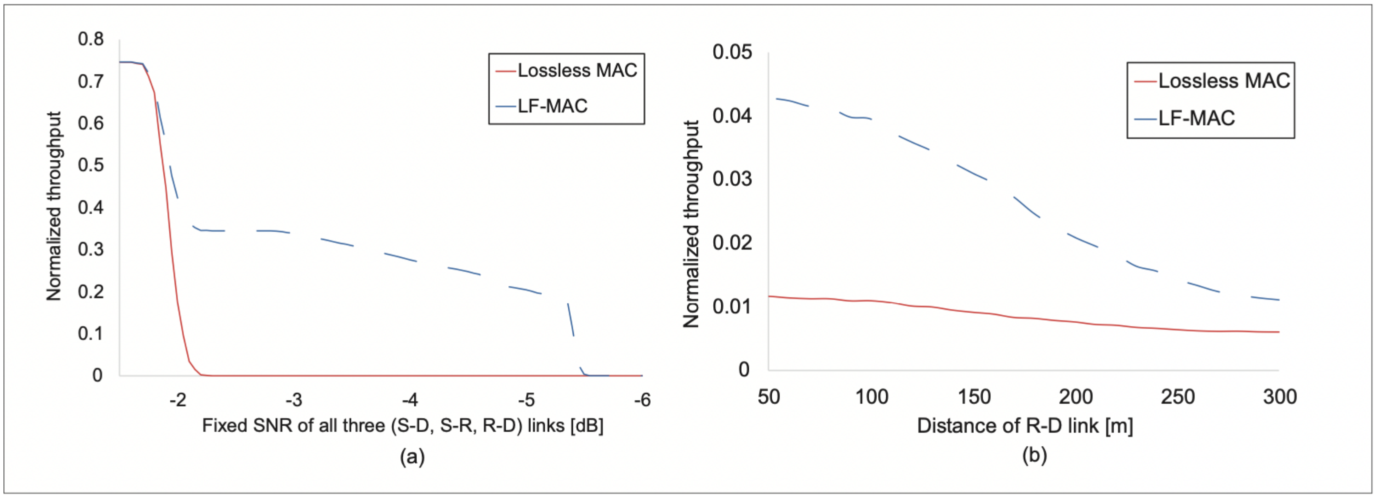

Fig. 6: (a) depicts throughput versus SNR ("Signal-to-Noise Ratio") graph, while (b) depicts throughput versus R-D link distance graph [1]

Functionality	Lossless MAC	LF-MAC
Erroneous frame handling	Discard	Forward (at relay) or store for later decoding (at destination)
Channel access	Same priority for source and forwarded messages	Priority access for forwarded data and Acknowledgment messages
Reliability approach	Per-hop stop-and-wait	End-to-end stop-and-wait
Acknowledgments	Sent over a single hop after each successful frame reception	Sent (by destination to source) after successful decoding at destination, possibly forwarded over multiple hops
Frame format	PHY header contains only modulation and coding scheme as well as PHY payload length	PHY header contains additional signaling information (including addresses) and separate checksum
Cross-layer flow	Traditional layered approach (including forwarding of error-free frames)	High degree of multi-layer cooperation

Fig. 7: Differences between conventional and lossy MAC [1]

If we observe the graph of PSR versus transmission powers, it is clear that LF-CBF has much better PSR and it reaches the 90 and 100 percent marks at lower transmission powers than CBF. This is possible because of the multiple relays and joint decoding involved in our technique. "With constant transmit power, the best improvement is at 17 dBm with 36.4 pp in PSR. On the other hand, if we demand a minimum PSR of 90 percent we have a gain of 6 dB in transmit power" [1].

The E2ED of LF-CBF is also observed to be lower at all transmitting powers. This is possible because in LF-CBF algorithm a node does not wait in case an erroneous packet is received, it forwards the packets irrespective of their error quality (Lossy Forwarding). Another factor is that the nodes that receive higher quality packets have lesser buffer times, further reducing the E2ED. "If the transmit power is under 7 dBm just a few packets reach the destination and therefore the statistics become worse and the error bars increase. With even lower transmit power no packets arrive at the destination" [1].

Another Important observation to be made is that PSR is the sum of number of packets required in the various decode attempts. Each decode attempt stops once a good quality packet is obtained or when one cycle of JD is completed at destination. As the transmission power depreciates, so does the quality of links involved. This brings the need for more decode attempts in order to obtain a good quality message at destination. For high powers of transmission ($> 33dbm$), 80 percent of the packets were obtained without errors in a single attempt. But, as the power decreases more number of attempts are required. As we can see for transmission power less than $25dbm$, the need for three decodes arises and here the LF-JD technique has a much higher PSR than normal CBF.

V. Conclusion and Future Scope

Thus we were able to propose Network (LF-CBF) and MAC (LF-MAC) protocols that can support lossy forwarding and joint decoding technique in cooperative communication. This technique is necessary in situations where prompt, reliable and efficient wireless communication is needed. The network nodes act as relays and forward information even if it is lossy, this makes the communication faster. At the destination, joint decoding helps to retrieve the original message using probabilistic algorithms, thus making the communication reliable. As more number of relays are use and multi-hop methods are incorporated, more received signal power is exploited which makes the whole process efficient. LF-JD is the next step in wireless communication. In Vehicular autonomous communication, low power, high speed and reliable transmissions are required in order to avoid hazardous situations. LF-JD provides the exact features needed in this example. The current protocols and methods cannot achieve the level of reliability and low-latency needed in cases of dynamic topology where the lossy link probabilities change rapidly. LF-JD can provide support in such cases with the use of multi-hop lossy forwarding. LF-JD has been able to avoid and reduce accident probability at intersections in experiments. Another future use of LF-JD can be in OTA radio technology. Thus, lossy forwarding and joint decoding can be used wherever

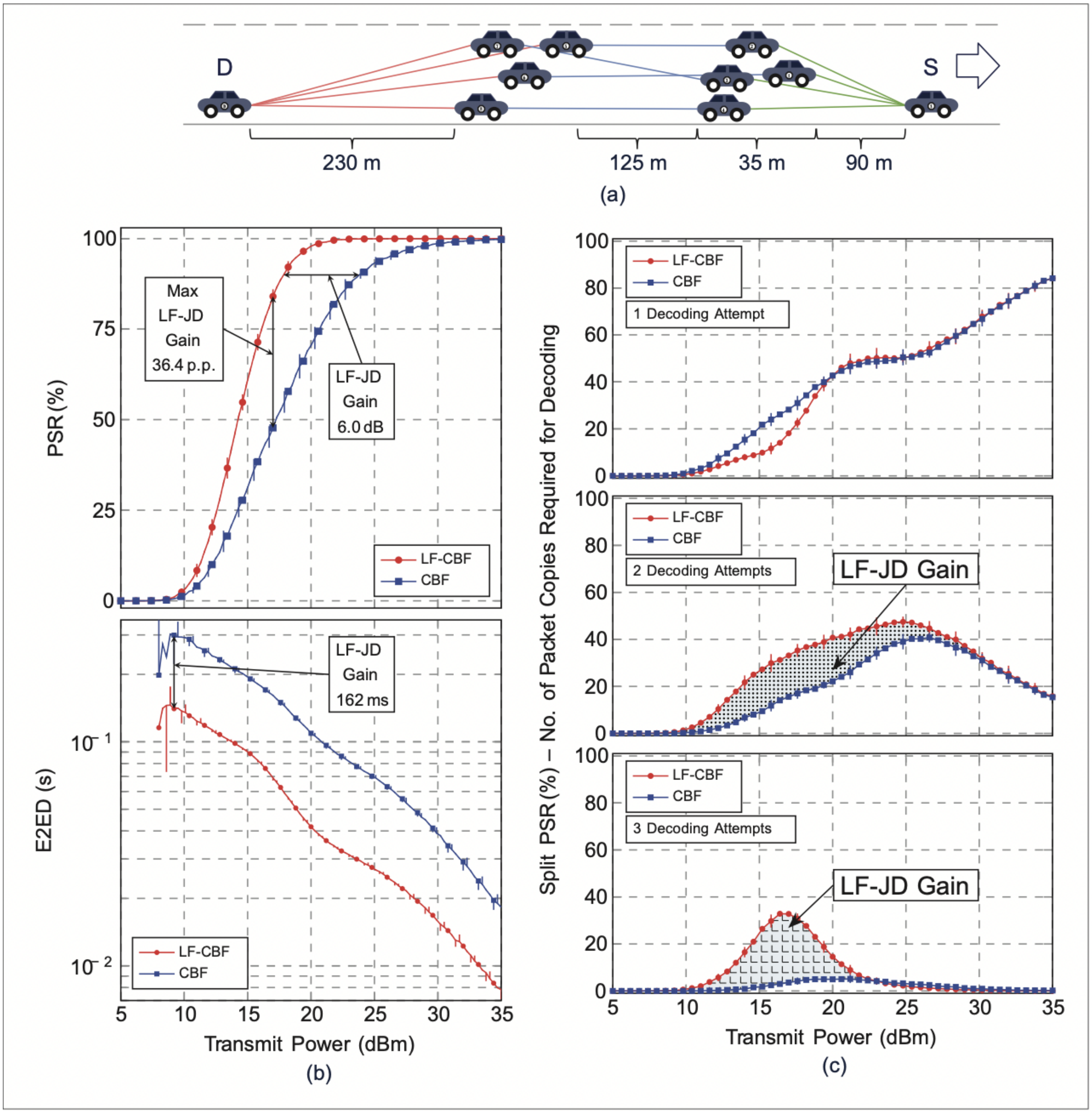

Fig. 8: (a) depicts topology of the 10 vehicles. (b) shows E2ED and PSR of LF-CBF and CBF. (c) shows splitting of PSR into three decode attempts [1]

there is a need for low energy, low latency and reliable wireless communication.

References

[1] S. Szott, S. Kuhlmorgen, V. Tervo, O. Adigun, M. Natkaniec and K. Kosek-Szott, "Impact of Lossy Forwarding on MAC and Routing Design in Wireless Ad Hoc Networks," in *IEEE Network*, vol. 33, no. 3, pp. 152-160, May/June 2019, doi: 10.1109/MNET.2018.1800061.

[2] R. A. M. Khan and K. Holger, "MAC Protocols for Cooper-ative Diversity in Wireless LANs and Wireless Sensor Net-works," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 1, 2014, pp. 46–63.

[3] K. Anwar and T. Matsumoto, "Accumulator-Assisted Distrib- uted Turbo Codes for Relay Systems Exploiting Source-Relay Correlation," *IEEE Commun. Lett.*, vol. 16, no. 7, 2012, pp. 1114–17.

[4] X. Zhou et al., "Distributed Joint Source-Channel Coding for Relay Systems Exploiting Source-Relay Correlation and Source Memory," *EURASIP J. Wireless Commun. and Net- working*, vol. 2012, 2012, p. 13.

[5] Taboga, Marco (2017). "Log-likelihood", Lectures on probability theory and mathematical statistics, Third edition. Kindle Direct Publishing. Online appendix. https://www.statlect.com/glossary/log-likelihood.

[6] V. Tervo et al., "An Error Rate Model of Relay Communi- cations with Lossy Forwarding and Joint Decoding," Proc. 2016 *IEEE Int'l. Conf. Commun. Workshops*, Kuala Lumpur, Malaysia, 2016.

[7] Intelligent Transport Systems (ITS); Vehicular Communica- tions; GeoNetworking (Part 1–6)," ETSI, 2013.

[8] M. Natkaniec et al., "D3.2. Report on Revised WP3 Archi- tecture Including Simulation Results," ICT- 619555 RESCUE, 2015.

[9] https://www.tutorialspoint.com/inter-frame-spaces-rifs-sifs-pifs-difs-aifs-eifs

[10] https://www.geeksforgeeks.org/what-is-arq-automatic-repeat-request/

[11] S. Kühlmorgen, A. Festag, and G. Fettweis, "Exploiting Dis- tributed Source Coding for Multi-Hop Routing in Wireless Ad Hoc Networks," *Proc. IEEE 83rd Vehicular Technology Conf. (VTC Spring)*, Nanjing, China, 2016.