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Impact of Lossy Forwarding on MAC and Routing Design in Wireless Ad Hoc Networks

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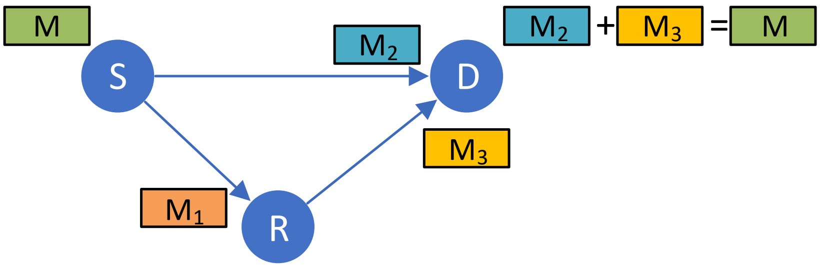
Abstract. Multi-hop ad hoc networks may employ cooperative communication, in which opportunistic relays use the spatial diversity of radio channels to increase communication reliability. An emerging variant of traditional relaying and forwarding schemes is the Lossy Forwarding–Joint Decoding (LF-JD) concept. In theory, LF-JD has shown the potential to improve spectral efficiency, reduce transmit power, and decrease outage probability by exploiting route diversity and the broadcast nature of radio transmissions. To be applied in real devices, a lower-layer protocol stack embracing the LF-JD concept needs to be designed. In this paper, we show how LF-JD impacts the design of MAC and routing protocols and whether its benefits translate to performance improvements. We show that, in comparison to currently available solutions, LF-JD can provide gains in scenarios with high interference or poor signal strength such as in vehicle-to-vehicle (V2V) networks.

Introduction

Recent advances based on information theory have led to the emergence of new paradigms in the area of wireless communications. Among them is the concept of cooperative communications, in which opportunistic relays are used to improve network performance [1]. Various forwarding strategies can be considered, e.g., amplify and forward or decode and forward [2]. However, a new alternative is based on the concept of lossy forwarding (LF) [3] in which relays decode and forward imperfect information, i.e., without performing message integrity checks. As a consequence, the destination may receive an erroneous message. By itself, such a message is useless, but joint decoding (JD) can be applied to multiple erroneous messages at the destination (e.g., in the form of distributed turbo coding [4]). Therefore, the combination of LF and JD (the LF-JD concept) can improve the reliability of communication in scenarios with lossy links, i.e., where links exhibit a high error probability [5].

Lossy radio links may be the result of a rapidly changing network topology. In such networks, performance can be improved by LF-JD, especially if retransmissions to the same user are difficult or not feasible. A good example is vehicle-to-vehicle (V2V) communications where LF-JD can improve safety applications such as road hazard and collision warnings. For these applications, the reliable and fast reception of messages is important to prevent incidents. With LF-JD the reliable communication range of vehicles can be extended; consequently, the driver has more time to react.

To illustrate the LF-JD paradigm we consider a cooperative communication scenario in which all links are lossy[1] (Figure 1a). This scenario is the simplest case of relay-assisted message transfer and consists of only three stations: the source (S), relay (R), and destination (D). S sends a message M which is concurrently received with errors (for the sake of this illustration) by stations R and D as M_1 and M_2, respectively. The received messages are different because S-R and S-D are independent radio links. By the definition of LF, R decodes M_1 and forwards it to D without checking if it contains errors. As a result, D performs JD using the two received messages, M_2 from the source and M_3 from the relay, trying to obtain the original message M. The next section provides further details of the operation of LF-JD.



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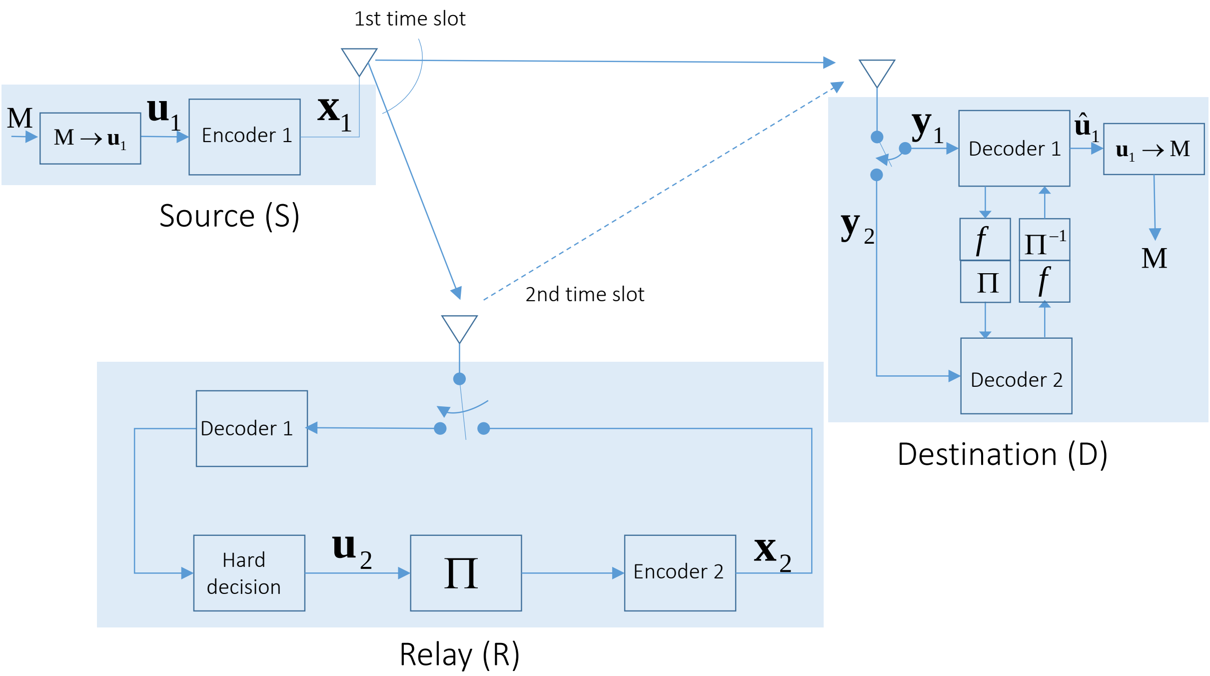


(b)

Figure 1. (a) An example of a basic cooperative communication scenario for the LF-JD concept with source (S), relay (R), and destination (D). Assuming all links are lossy, each transmission is received with errors. For example, M is received at R as M_1, which, when forwarded, is received at D as M_3. Joint decoding of all received message copies potentially allows retrieving the original M. (b) A schematic diagram of coding in LF-JD in this scenario. The interleaver and deinterleaver blocks at the relay are denoted as Π and Π^{-1}, respectively. The LLR update function is denoted as f.

[1] The LF-JD paradigm applies when at least one link is lossy on each path between the source and destination. If not, conventional communication occurs.

In practice, more than one relay may be involved in the message exchange, which may also involve multiple hops. Therefore, cooperative communication impacts both scheduling of cooperating nodes as well as topology management and maintenance. Cross-layer support is therefore required during the design of medium access as well as routing. Multiple MAC communication protocols have been proposed in the literature for cooperative scenarios [1]. However, none of them has considered the LF-JD paradigm, which has thus far only been analyzed at the physical (PHY) layer. Similarly, packet recovery techniques for lossy links have been designed, e.g., based on retransmitting damaged parts [6] or with improved forward error correction [7]. However, they do not exploit cooperative transmissions.

Analyzing the scenario in Figure 1 from an information theoretic perspective the LF-JD paradigm seems deceptively easy to exploit. Indeed, in theory LF-JD has shown the potential to improve spectral efficiency, reduce transmit power, and decrease outage probability [3, 4, 5]. However, it has specific implications which need to be addressed when designing a dedicated lower-layer protocol stack. In particular, the following questions are relevant:

- What are the network topologies envisaged? What are the signaling and routing requirements?
- Does LF-JD require control information to be sent, e.g., acknowledgments or channel state information?
- Does the concept require any auxiliary information, e.g., information about the S-R link to be used in decoding at D, to be transferred along with the message?
- How should the data link layer incorporate fault management, e.g., decoding errors?

In this paper, we describe the LF-JD concept as a variant of traditional relaying and forwarding schemes. We explain how this impacts the design of protocols above the physical layer. We describe the first design of a MAC and routing protocol which specifically address the requirements imposed by LF-JD. Then, we evaluate the proposed protocols through simulations to show use cases for the LF-JD paradigm. Finally, we conclude with lessons learned from this design.

Technical Background

LF-JD is a cooperative communication paradigm extending decode and forward relaying by allowing intra-link errors which, combined with distributed turbo coding (DTC), brings improved error protection. The relays decode and re-encode the data, and even with possible decoding errors at the relays, the forwarded message copies received by the destination are correlated. This correlation can be taken into account when decoding at the destination. The fundamentals of LF as a relaying strategy have been introduced in [3, 4]. In this paper, the analysis is carried out by using the error rate model presented in [5], which has been parametrized to imitate the error rate performance of the coding structure introduced in [3, 4].

In the DTC concept, each sender applies an interleaving pattern to its source sequence before encoding. Due to the correlation between the sequences, the differently encoded copies can be combined by iterative decoding. Here, we assume that the senders can be relays that are forwarding the original source sequence. Thus, even though the quality of the individual links is not sufficient, the end-to-end communication may still be successful by utilizing route diversity combining. This can be achieved by utilizing a bit-wise reliability compensation function that employs the knowledge of the error probabilities at the relays. The DTC and joint decoding structure is found to be supported by the correlated source coding theorem (Slepian-Wolf theorem) in network information theory [8]. It states that if the rate set supported by the channels falls into the admissible region, the transmitters can independently encode and transmit the information sequences to the destination with arbitrary low probability of error. The destination is able to perfectly reconstruct the original information by performing joint decoding for the sequences received from all transmitters.

A schematic diagram of the three-node case for LF-JD is shown in Figure 1b. During the first time slot, S broadcasts the encoded sequence $\mathbf{X}_1$ to R and D. In LF-JD, R decodes making hard decisions, interleaves, and re-encodes the data sequence before forwarding the signal. Hard decisions are used because sending the soft information to the destination would be inefficient. Instead, reliability information is sent in the form of a single parameter as explained in the next paragraph. Interleaving is used to ensure that there are independent sources of extrinsic information for joint decoding at the destination. During the second time slot, R sends the differently encoded sequence $\mathbf{X}_2$ to D. At D, the sequence $\mathbf{Y}_1$, received directly from the source, is guided to decoder 1 and $\mathbf{Y}_2$, the sequence received from the relay, is guided to decoder 2.

If the information sequence after decoding at R contains errors, these errors can easily cause interference in the joint processing of the sequences at the destination. However, this interference can be significantly reduced if D can use some sort of information about the channel between S and R. Joint decoding in LF-JD uses reliability information in the form of the bit error probability at R. This bit error probability is used to update the information that is exchanged between the constituent decoders in the form of log-likelihood ratios (LLRs). The bit error probability can be estimated at R and transmitted to D inside the frame header or it can be estimated during the joint decoding process.

The theoretical background of the one-way relaying system allowing intra-link errors can be related to source coding with a helper [9]. In such a case, S aims to transmit the information sequence $\mathbf{u_1}$ as shown in Figure 1b, and D aims to recover $\mathbf{u_1}$ with aid of the helper information $\mathbf{u_2}$, which, in this case, is an erroneous version of the original sequence $\mathbf{u_1}$. In our JD implementation, decoders at D have inputs from the channel as well as from each other in the form of LLRs. Because the information sequences $\mathbf{u_1}$ and $\mathbf{u_2}$ may be different, the reliability of the exchanged information has to be taken into account. This is performed by updating the LLRs with function f using the probability that the information bits transmitted from S and R are different. Because we are only interested in the sequence $\mathbf{u_1}$ transmitted from S, the output of JD is the estimate $\hat{\mathbf{u}}_\mathbf{1}$ which can be obtained after the convergence of the JD process.

The complexity of LF-JD depends on the component codes used at the source and relay, i.e., encoder 1 and encoder 2, respectively. JD is basically a turbo decoder with an added LLR update function. Efficient hardware implementations for turbo decoders exist, however, the LLR update function is not considered in state-of-the-art implementations.

The main motivating factors for applying the LF-JD paradigm are:

- **Route diversity**. The signal is delivered via multiple disjoint paths. Thus, the probability of successful reception increases.

- **Broadcast nature of radio transmissions**. Multiple relay stations capture the original transmission and thus more of the received signal energy is exploited.
- **Lossy forwarding.** Unlike in conventional decode and forward, in which relays forward only error-free packets, LF can use also relays that have decoded packets with errors. A higher portion of the received signal energy is therefore exploited.
- **Distributed turbo codes and iterative decoding**. The parallel relays together form a powerful low rate forward error correction code, which operates close to Shannon capacity. The decoder at the destination utilizes source correlation as it knows that the data received via different routes is essentially the same (the original message M).

From the above description of LF-JD it becomes evident that any implementation of this concept requires two important functionalities. First, appropriate scheduling of channel access is required to organize the transmission of the source and relays. Second, signaling is required to allow the destination to uniquely identify arriving message copies. These functionalities are provided by the designed MAC protocol.

Lossy Forwarding MAC

The objective of the lossy forwarding MAC (LF-MAC) is to define medium access rules to ensure successful frame transmission in a network with lossy links. While the description below follows the example topology of Figure 1, LF-MAC is designed to support scenarios with multiple relays as well as multi-hop transmissions [10]. For LF-MAC we have decided to build upon carrier sense multiple access with collision avoidance (CSMA/CA). Since even the most basic cooperative communication scenario involves three communicating stations where messages are received simultaneously, we assume that from a MAC-layer perspective all frames are broadcast. The forwarding decision is distributed: after receiving a message, each station decides if it should serve as a relay. This decision is based on two factors: the quality of the received frame and the placement of the potential relay on a path towards the destination as determined by the routing protocol (described in the next section). Taking into account these assumptions LF-MAC defines:

- the basic cross-layer data flow at each station,
- a new header format,
- rules for medium access based on CSMA/CA,
- a method to ensure reliable end-to-end delivery of messages.

LF-MAC is the first MAC protocol embracing the LF-JD principle and serves as a starting point for further development. It is designed so that cooperation with additional control mechanisms (e.g., rate control algorithms, advanced error control methods, routing protocols) is possible [10]. These additional mechanisms can further improve network performance in larger topologies but their description is out of the scope of this paper.

Data Flow

Figure 2a presents the data flow for the transmission of a single message. At the source, each OSI layer adds its own header to the message as it is passed down the protocol stack. To enable LF-JD, we modify the data link and physical layers while maintaining full compatibility with higher layer protocols (such as the Internet Protocol, IP).

Each data message requires error-free meta-data (such as its destination) so that it can be processed by a receiving station. This meta-data is attached at the last moment before transmission: within an extended PHY header with a total size of 31 bytes[2] protected against errors using a coding rate of 1/4 (Figure 2b).

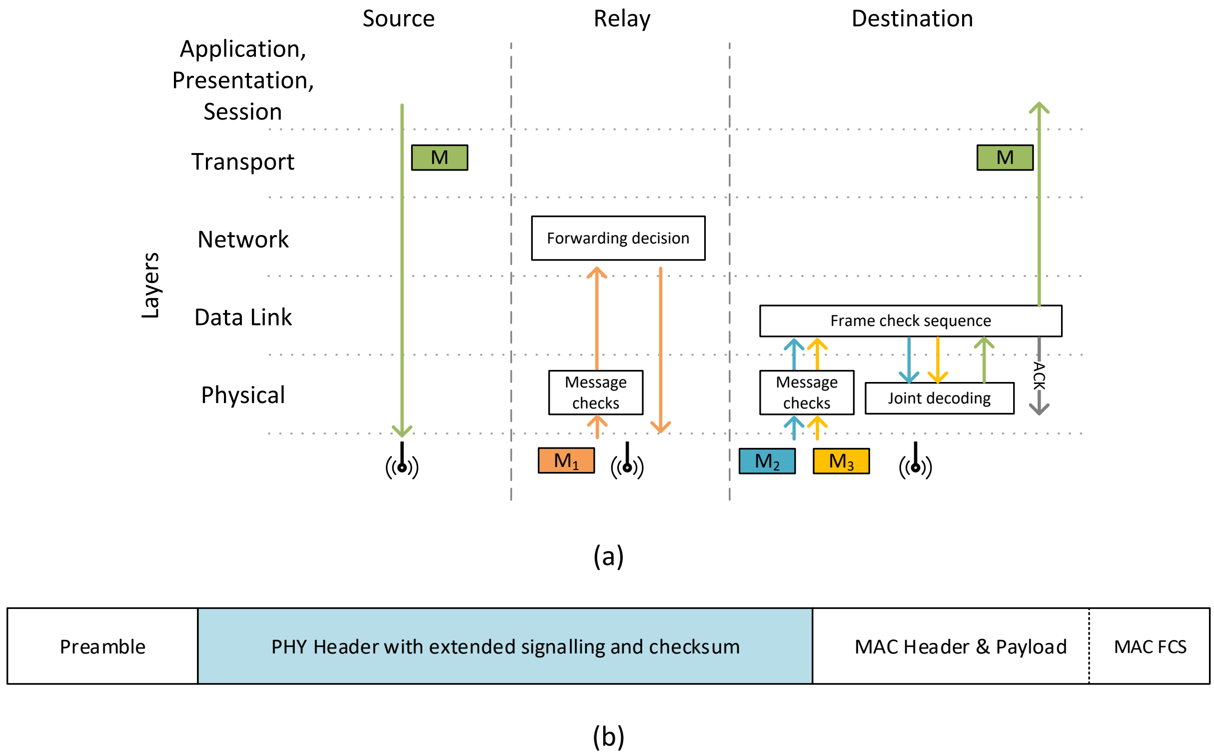


Figure 2. (a) Cross-layer data flow in the scenario described in Figure 1. (b) Format of data message where the LF-JD paradigm requires extending the PHY header (shaded block) with additional signalling and a PHY header checksum.

We assume that the data message M, transmitted by the source, is received at the relay and destination *with errors*. Two message checks are conducted upon reception. First, the integrity of the PHY header is checked to ensure that the supplemental meta-data is error-free. Second, the quality of the decoded message is evaluated: only messages with an estimated bit error rate below a predefined threshold are passed to higher layers[3]. *At the relay*, the routing protocol performs a forwarding decision based on the addresses contained in the PHY header of the received message copy and, if needed, passes the message to the lower layers for transmission. In parallel, *at the destination*, the two message checks (PHY header integrity and message quality) are also performed. Then, the message's end-to-end integrity is checked based on the frame check sequence (FCS) at the MAC layer[4].

[2] This header size could potentially be further reduced, even in this configuration LF-JD shows performance improvements. For short packets, the LF-JD method could simply be switched off.

[3] In terms of channel occupancy, it is better to attempt a retransmission from the source, than to forward a message with a high bit error rate.

[4] Note that relays do not need to perform this check.

If errors are detected and the test fails, this first message copy (M_1) is stored in a repository and the destination awaits the arrival of further copies. When M_3 arrives from the relay, its FCS is also checked. Upon failure, M_3 is stored in the repository which triggers a JD procedure. Both message copies are identified as related based on their PHY headers. The FCS of the jointly decoded message is verified and, if positive, the message can be passed up the protocol stack. Otherwise, the destination awaits further copies until they can all be jointly decoded to provide an error-free message or a predefined timeout expires (independent of the number of message copies), after which the stored copies are dropped.

To inform the source that a message has been correctly received, an end-to-end acknowledgement (ACK) is sent after a positive FCS verification. The ACK is a short message, comprising only a PHY header, which can be associated with the data message that it acknowledges. A description of the reliability features of LF-MAC is provided later on.

Frame Format

The LF-JD paradigm requires that the PHY header is extended with auxiliary information (Figure 2b). This includes three address fields (source, sender, and destination) – each containing relevant MAC addresses. These were chosen to simplify the addressing, although shorter addresses may be used in practice. The source and destination designate the message's end-to-end stations, while the sender is the transmitter of this particular frame (e.g., a relay). Consecutive messages are distinguished by a sequence field. A confidence indicator field is used to describe a frame's quality defined as the bit error probability after decoding. This probability can be directly estimated from the output LLRs of the decoder and it is used during JD. A field containing the interleaver index is also necessary for the operation of the decoder. Finally, a checksum field allows detecting errors in the header itself, which has to remain error-free. The PHY payload contains the MAC frame, which is not guaranteed to be error-free (before successful JD at the destination). Therefore, the contents of the MAC header remain unchanged. The MAC frame ends with the FCS to enable the destination to confirm a successful JD before passing the frame to higher layers.

The end-to-end ACK has a format similar to the described data format except that it consists only of a PHY header containing the indispensable fields to make it as short as possible. The ACK can be associated with its corresponding data message based on the three-tuple of source address, destination address, and sequence number. The full specification of all frame types is available in [10].

Channel Access

The channel access procedure defined for LF-MAC is partially similar to that of IEEE 802.11. For the scenario illustrated in Figure 1 it is the following. First, the source waits until the channel has been free for a long inter-frame space (LIFS) period and then transmits after a random number of backoff slots (as in CSMA/CA). As a result, the erroneous DATA message is simultaneously received by the destination and relay. Then, the relay, after a random backoff time (to avoid collisions with other potential relays) transmits the received message. If collisions do occur, relays attempt to retransmit unacknowledged messages. When enough copies of the message are received at the destination to successfully jointly decode the initial DATA message, the destination sends the end-to-end ACK after waiting a short inter-frame space (SIFS) period.

Reliability

A simple stop-and-wait automatic repeat request (ARQ) protocol is implemented as part of LF-MAC. It provides end-to-end acknowledgments with a configurable ACK waiting time at the source. After restoring the original frame at the destination, LF-MAC transmits an ACK frame after the SIFS period without performing any backoff procedure. Acknowledgment frames may be forwarded by relays, but only after an obligatory backoff to reduce the risk of collisions. To further reduce the intensity of transmissions, additional mechanisms (such as giving strict priority to ACK transmissions and having relays replace lower quality messages by higher quality ones) have been defined [10]. While the stop-and-wait solution is appropriate for small topologies (Figure *1*), providing reliability in larger topologies requires more advanced ARQ protocols [10]. They are not covered here due to space limits.

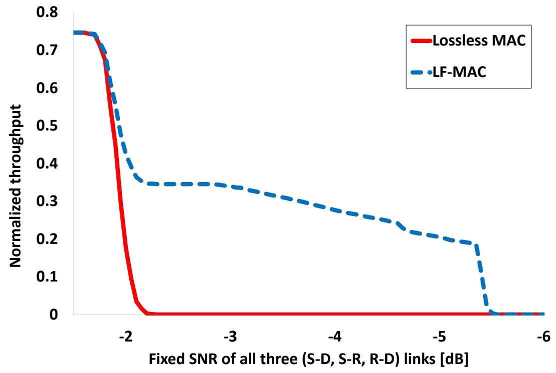
Validation of LF-MAC

We have implemented LF-MAC in the ns-3 simulator, using an abstraction[5] of the underlying JD scheme [5], and compared its performance to a CSMA/CA-based lossless MAC protocol in the topology of Figure 1. The difference between the two approaches is summarized in Table 1. In Figure 3a, we consider a fixed loss channel model, where we decrease the link quality of all three links from lossless conditions to complete loss of communication. The results show that there exists an *area of operation* in terms of channel quality, where the LF-JD paradigm provides connectivity in contrast to traditional communication. In a more realistic model with Nakagami fading (Figure 3b), we set the S-D and S-R distances to 300 m so that both these links are lossy. We then varied the R-D distance so that the link changed, as previously, from lossless to lossy conditions. Now, the comparison between LF-MAC and lossless MAC is less discriminatory, but still shows a meaningful performance increase. Further results, including a reliability analysis, are available in [10].

Table 1. Comparison of differences between traditional lossless MAC and LF-MAC design.

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 acknowledgement messages
Reliability approach	Per-hop stop-and-wait	End-to-end stop-and-wait
Acknowledgements	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

[5] https://mns.ifn.et.tu-dresden.de/Research/Projects/Pages/RESCUE.aspx



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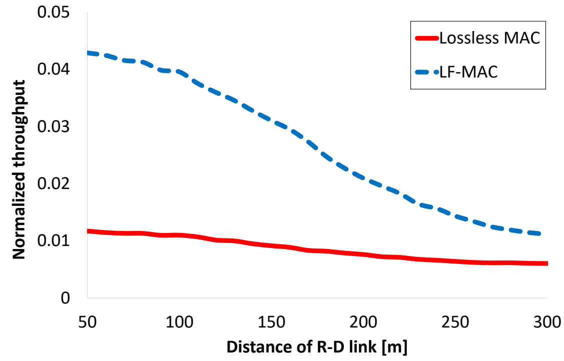

(b)

Figure 3. Comparison of LF-MAC and lossless MAC performance under saturation in the topology of Figure 1: (a) throughput for the fixed channel loss model, where the fixed SNR value describes the quality of all three links (S-D, S-R, R-D); (b) throughput for the Nakagami fading channel model, the S-D and S-R distances are set to 300 m (lossy links) and the distance of the R-D link is variable *[10]*.

Routing with LF-JD

The previous section described LF-MAC, which defines the medium access. In this section we focus on the network layer, its forwarding algorithms, and their applicability to multi-hop networks. The standardized access layer ITS-G5, a European standard based on IEEE 802.11p, was used for our evaluation.

Topology management is an essential requirement for the LF-JD paradigm to operate in multi-hop networks. Thus, integrating this concept with a routing protocol is necessary. We use georouting as a convenient example. It is a network-layer protocol for mobile ad-hoc networks, which takes into account the geographical location of stations. One algorithm used in georouting is contention-based forwarding (CBF) where timers and overhearing determine the forwarding process [11]. To deploy the LF-JD paradigm, CBF had to be extended as described below.

CBF is used to forward a packet to a dedicated destination or geographic area. It is a receiver-based forwarding algorithm where the source broadcasts the packet to all neighbors and they decide to forward the packet or drop it. This approach is in line with the cooperative communication requirements of LF-JD (as described in the previous section). Receivers with a positive geographical progress, i.e., which are closer to the destination than the sender, buffer the packet and start a timer depending on the progress. A station with a greater progress has a shorter timer. When the timer expires the packet is re-broadcast to all neighbors. If a station receives the same packet a second time before the timer expires (overhearing a transmission from a better-positioned neighbor), it removes this packet from the buffer and stops the timer.

In CBF, received packet duplicates are dropped. Hence there is only one route to the destination. To support LF-JD, we have to address several requirements to guarantee that more than one packet copy with uncorrelated errors arrives at the destination. We propose LF-CBF [12] which supports the following features:

1. **Multipath distribution:** Relays are allowed to re-broadcast packet copies. A retransmission counter is incremented upon reception of each packet copy. Arriving packet copies are dropped once the counter exceeds a retransmission threshold. This ensures forwarding over multiple paths and the destination receiving multiple copies to enable JD.
2. **Selective forwarding of packet copies:** Relays select the best packets for forwarding. For successful joint decoding, the errors within packet copies need to be uncorrelated. This requires storing information of the path traversed by the packet (two previous senders proved sufficient in our case) in the PHY header. This allows relays to differentiate packets so that copies with correlated errors are not forwarded.
3. **Timer computation:** Relays compute the timeout according to the packet's confidence value – provided from the PHY, which estimates the number of errors inside the packet. Thus packets with fewer errors have a shorter timeout. A packet failing to reach a quality threshold is dropped.
4. **Avoidance of incorrect discarding:** Packets with negative destination progress are not considered in duplicate detection allowing subsequent packets to be forwarded.

The flow diagram of LF-CBF is presented in Figure 4.

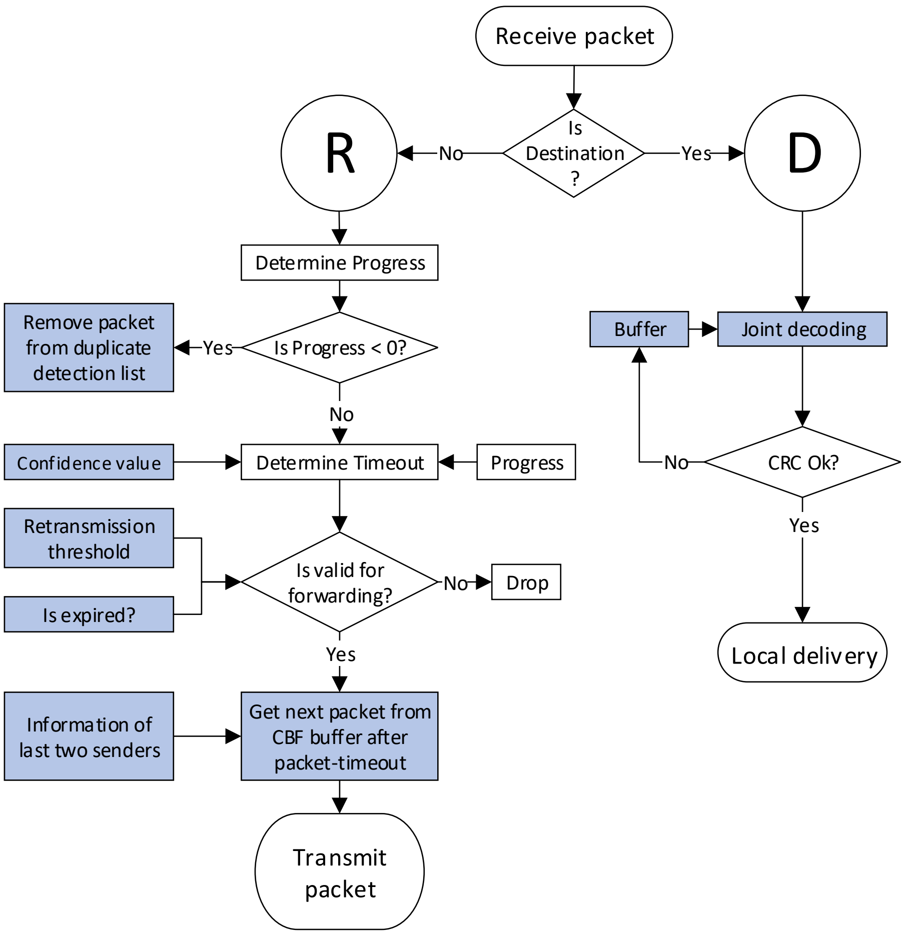

Figure 4. Flow diagram of LF-CBF. Providing routing with the LF-JD paradigm requires adding the shaded blocks to CBF.

Validation of LF-CBF

We evaluate LF-CBF's performance by comparing it to the standard-based CBF [11]. Using the ns-3.19 simulation tool, we compared the algorithms according to their packet success ratio (PSR) and end-to-end delay (E2ED). PSR, the number of packets successfully received at the destination divided by the number of packets transmitted by the source, is a measure of reliability. E2ED is the difference between the timestamp when the message is generated by the source and the timestamp when it is received by the destination averaged over the travel time of all received messages.

We considered a typical freeway scenario with sparse station density (Figure 5a). To show the best gain of the LF-JD paradigm, a platooning scenario with two small groups of vehicles was chosen. The groups consisted of four cars each. They served as the packet relays. One source sent packets to a single destination. The source and destination were placed before and after the two groups of vehicles, respectively (giving a total of 10 vehicles in the network). By varying the transmit power of each vehicle the quality of their communication links changes. By decreasing the transmit power, consequently, the probability of lossy links increases.

In Figure 5b we observe that LF-CBF outperforms CBF over the whole range of evaluated transmit powers. Up to 23 dBm, LF-CBF has a PSR of 100%, which is crucial for the correct operation of V2V safety applications. CBF achieves less than 100% up to 35 dBm. With constant transmit power the most improvement is at 17 dBm with 36.4 pp in PSR. On the other hand if we demand a minimum PSR of 90% we have a gain of 6 dB in transmit power. These performance improvements are a result of using multiple links along with JD as enabled by LF-CBF.

LF-CBF also has a shorter E2ED for all transmit power values since in lossy forwarding all packets are relayed even if they are corrupted. In CBF, if a packet is not received correctly it is dropped and we have to wait until further timers of other stations expire and they re-broadcast the packet again, which leads to a longer E2ED. The second reason for the reduced E2ED is that also the link quality is taken into account. A good link (i.e., one with a high confidence value) has a shorter timer, which also reduces 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.

Figure 5c presents the PSR versus transmit power for a different number of packets used for decoding attempts for either lossy forwarding with joint decoding (LF-CBF) or the number of packets until an error-free packet arrives. The sum of all three curves for either CBF or LF-CBF represents the PSR of Figure 5b. We can see that for a high transmit power beyond 33 dBm over 80% of packets were decoded correctly with a single copy only (top graph in Figure 5c). With decreasing transmit power also the ability to decode a packet error-free with only one copy decreases and a second copy is needed. Therefore, the curves where two decoding attempts are necessary increases for lower transmit power (middle graph in Figure 5c). At approximately 25 dBm also the LF-CBF curve for three decoding attempts becomes important and increases up to 33% at 16.7 dBm (bottom graph in Figure 5c). Against the baseline given by the CBF curve, the LF-CBF curve represents the gain achieved by applying the LF-JD concept to georouting. Further performance results, including overhead analysis, can be found in [12].

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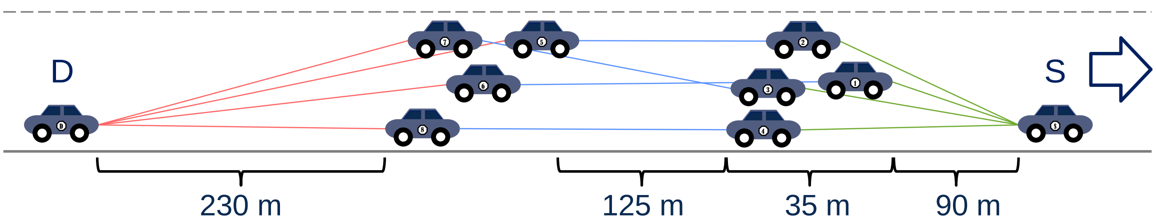

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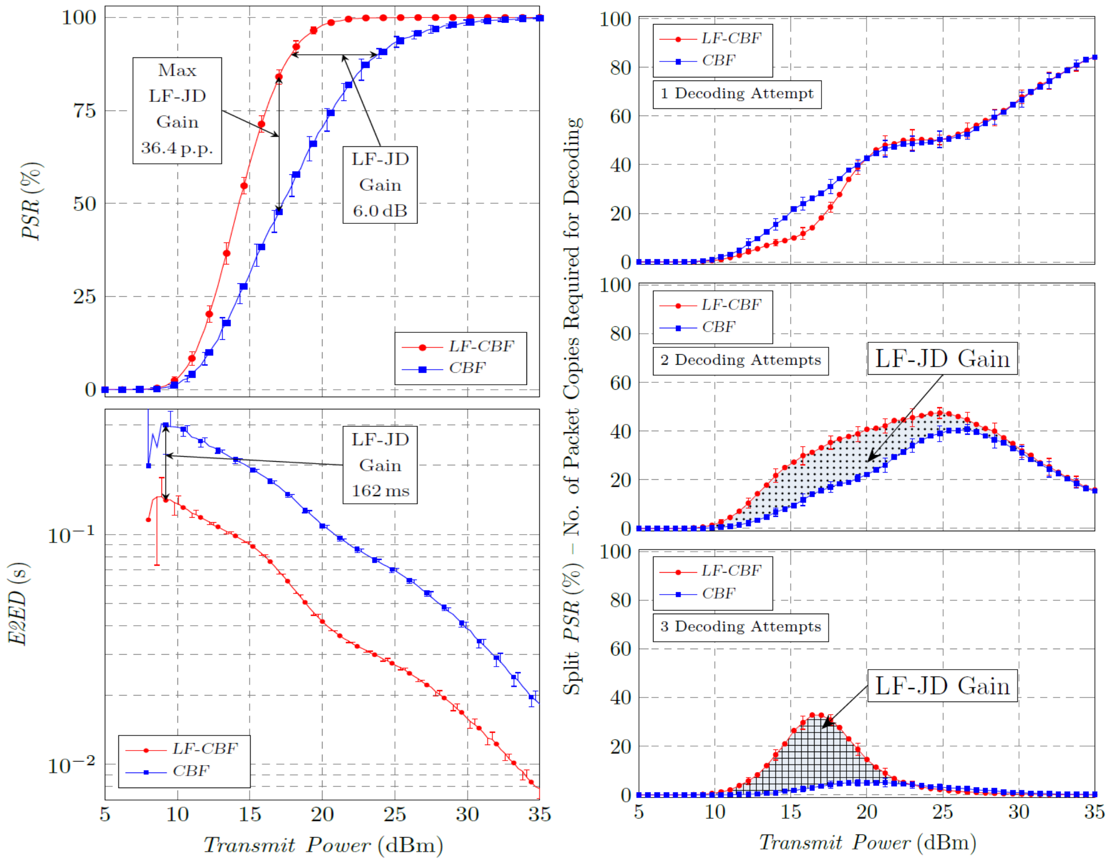

(b) *(c)*

Figure 5. LF-JD gain in the V2V scenario: (a) topology of considered scenario, (b) PSR and E2ED, (c) PSR split according to the number of packet copies required for successful decoding.

Summary

We have presented the LF-JD paradigm as a cooperative communication model which has the potential to improve spectral efficiency, reduce transmit power, and decrease outage probability by exploiting route diversity and the broadcast nature of radio transmissions. In LF-JD, opportunistic relays decode and forward messages across multiple disjoint paths between source and destination. These messages are then successfully combined using joint decoding at the destination. In this paper, we have provided the first lower-layer protocol stack (MAC and routing) which supports the concept of LF-JD. The evaluation confirms that, subject to the availability and placement of potential relays, communication quality can be improved in scenarios with high interference or poor signal strength.

The abovementioned features of LF-JD are especially important for vehicular networks where the topology changes frequently and safety applications demand short latency and high reliability. In challenging communication conditions, where retransmissions take too long or are not possible at all, such demands cannot be achieved by current technologies such as 802.11p. In [13], we investigated an intersection scenario and were able to show that joint decoding is able to improve both reliability and communication range, leading to significantly less accidents at the intersection. We have also designed and evaluated the LF-JD concept in a coordinated CSMA/CA setting [14]. An open research area is to extend the validation of the LF-JD paradigm to experiments with over-the-air radio equipment. Using SDR devices we have conducted preliminary lab tests and field trials as outlined in [15], but further research is required.

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