Opportunistic Routing Metrics: A Timely One-Stop Tutorial Survey

Mostafa Abdollahi, Student Member, IEEE, Farshad Eshghi, Member, IEEE, Manoochehr Kelarestaghi, Member, IEEE, Mozafar Bag-Mohammadi

Abstract—High-speed, low latency, and heterogeneity features of 5G, as the common denominator of many emerging and classic wireless applications, have put wireless technology back in the spotlight. Continuous connectivity requirement in low-power and wide-reach networks underlines the need for more efficient routing over scarce wireless resources, in multi-hop scenarios. In this regard, Opportunistic Routing (OR), which utilizes the broadcast nature of wireless media to provide transmission cooperation amongst a selected number of overhearing nodes, has become more promising than ever. Crucial to the overall network performance, which nodes to participate and where they stand on the transmission-priority hierarchy, are decided by user-defined OR metrics embedded in OR protocols. Therefore, the task of choosing or designing an appropriate OR metric is a critical one. The numerousness, proprietary notations, and the objective variousness of OR metrics can cause the interested researcher to lose insight and become overwhelmed, making the metric selection or design effort-intensive. While there are not any comprehensive OR metrics surveys in the literature, those who partially address the subject are non-exhaustive and lacking in detail. Furthermore, they offer limited insight regarding related taxonomy and future research recommendations. In this paper, starting with a custom tutorial with a new look to OR and OR metrics, we devise a new framework for OR metric design. Introducing a new taxonomy enables us to take a structured, investigative, and comparative approach to OR metrics, supported by extensive simulations. Exhaustive coverage of OR metrics, formulated in a unified notation, is presented with sufficient details. Self-explanatory, easy-to-grasp, and visual-friendly quick references are provided, which can be used independently from the rest of the paper. Finally, a new insightful framework for future research directions is developed. This tutorial-survey has been organized to benefit both generalists and OR specialists equally, and to be used not only in its entirety but selectively as well.

Index Terms—Opportunistic routing; Metric; Multi-hop; Wireless network; Ad hoc; Wireless sensor network; Transmission cooperation; Candidate forwarder list.

I. Introduction

Routing, the process of choosing the (possibly) most cost-efficient path(s) between two endpoints in a multi-hop network, has long been of special interest to network researchers. The routing process is one of the main functionalities of the network layer. Different modes of transmission (uni/broad/multi/any-cast) combined with the consideration of various factors, such as traffic volume and type, number of hops, node density, mobility, energy requirements, and Quality of Service (QoS), have led to the creation of different routing algorithms/protocols. Early routing algorithms were introduced for wired networks. Thus, they were adapted to specific characteristics of those networks, such as low-error/high-bandwidth links and point-to-point (unicast per link) packet delivery mode.

In recent years, a variety of Wireless Networks (WNs) have been deployed extensively due to their ease of access, large areas of applicability, low set-up cost, and fast implementation. On the other hand, the prevalence of multi-hop-in-nature wireless infrastructures in Wireless Mesh Networks (WMNs), the delivery of information at a limited number of sink nodes in Wireless Sensor Networks (WSNs), the ubiquitous connectivity requirement in the context of the Smart City [1], the topology variation and geographical spread of Vehicular Ad hoc Networks (VANETs) [2], [3], the emerging Vehicular Energy Networks (VENs) [4], and Unmanned Aerial Vehicles Networks (UAVNETs, also called Flying Ad hoc Networks (FANETs)) [5], [6], [7], the enormity of low-power devices in IoT [8], [9], the D2D communications [10], [11] support in 5G [12], and the ad hoc networks of secondary users in cognitive wireless networks [13] all raise serious demands for more promising multi-hop routing protocols in wireless networks (Fig. 1).

The WNs are characterized by high-error/low-bandwidth links, time-varying, and multi-path communication channels, a broadcast medium (which implies that all nodes within radio range hear each other), a tight power budget, and possibly mobile nodes. These characteristics require a custom-designed dynamic routing algorithm/protocol. Other than the higher dynamics due to mobility and time-varying link qualities, traditional wireless routing, i.e., the single-path routing, does not differ substantially from wired networks routing. In single-path routing, the route information generated through the route discovery process is included in the packet header. The route information determines how a packet traverses a single path, hop-by-hop, towards the final destination.

The rest of this paper is organized according to Fig. 2. To make this work more useful, even for generalists, we start with a self-explanatory tutorial, including background on diversity in wireless, a description of OR, the OR history, and finally, the OR metric design process. The second section, a survey on OR metrics, starts with the motivation for and the contributions of this work. The section continues with a classification of OR metrics presented in section II.C. After that, a complete collection of OR metrics is classified and...
II. OR Metric: A Tutorial

A. Background

The unreliability of wireless links necessitates considering extra provisions, particularly in multi-hop applications. Employing diversity can mitigate the unreliability by benefiting from the broadcasting nature of the wireless medium. In the wireless literature, there are two different, though somewhat close, points of view regarding diversity. The first point of view regards diversity as having a variety of available wireless transmission means and choosing the best one. Some related techniques are Multi-user Diversity Forwarding (MDF) and Selection Diversity Forwarding (SDF), which choose from the available multiple transmitter-receiver pairs and downstream forwarders, respectively [14]. The second point of view regards diversity as the collaboration or cooperation between various transmission means. In the context of OR, we stick to the latter approach in what follows.

To provide a structured diversity discussion, we opt to present it in the framework of the TCP/IP network protocol stack. As Fig. [3] suggests, the diversity in wireless transmission can be introduced in the three bottom layers of the network protocols stack. It is essential to note that diversity implementation is described using the introduced unified notation in Table [III]. In section [III-D], two easy-to-use quick-reference tables and one timeline illustration are presented. A simulation comparison between main representatives of OR metric classes, and a discussion of implicit and difficult-to-notice network performance dependencies appear in section [III-E]. Some fundamental and critically important questions regarding OR metric computation, in general, and some specific OR metrics are raised in section [III-F]. Ideas for future research opportunities are proposed in section [IV]. The concluding remarks complete the discussion.
TABLE I: List of acronyms.

| Acronym   | Description                                      |
|-----------|--------------------------------------------------|
| ACK       | Acknowledgement                                  |
| BS        | Base Station                                     |
| CPS       | Cluster Parent Set                               |
| CR        | Cognitive Radio                                  |
| CRAHN     | Cognitive Radio Ad-Hoc Networks                  |
| DFS       | DCF Interframe Space                             |
| DLL       | Data Link Layer                                  |
| EOFT      | Energy Objective Function                        |
| FANET     | Flying Ad hoc Networks                           |
| IoT       | Internet of Vehicles                             |
| LQI       | Link Quality Indicator                           |
| MANET     | Mobile Ad hoc Network                            |
| MIMO      | Multiple-Input and Multiple-Output              |
| MPR       | Multi-Path Routing                               |
| NC        | Network Coding                                  |
| OFDM      | Orthogonal Frequency Division Multiplexing       |
| PDP       | Packet Delivery Probability                      |
| QoS       | Quality of Service                               |
| RTT       | Round-Trip Time                                  |
| SDF       | Selection Diversity Forwarding                   |
| STC       | Space-Time Coding                                |
| UAWSN     | Acoustic Wireless Sensor Network                 |
| UWNSN     | Underwater Wireless Sensor Networks              |
| VANET     | Vehicular ad hoc Networks                        |
| WN        | Wireless Networks                                |
| WSN       | Wireless Sensor Networks                         |
| APR       | Alternate-Path Routing                           |
| CFS       | Candidate Forwarding Set                         |
| CR-SIoT   | Cognitive Radio Social Internet of Things        |
| CRN       | Cognitive Radio Networks                         |
| D2D       | Device-to-Device                                 |
| DL        | Deep Learning                                    |
| DS-CDMA   | Direct Sequence-Code Division Multiple Access    |
| EWMA      | Exponential Weighted Moving Average              |
| IoT       | Internet of Things                               |
| LIVE      | Link Validity Estimation                         |
| MAC       | Medium Access Control                            |
| MDF       | Multi-user Diversity Forwarding                  |
| ML        | Machine Learning                                 |
| NB-IoT    | Narrowband Internet of Things                    |
| NET       | Network Layer                                    |
| OR        | Opportunistic Routing                            |
| PHY       | Physical Layer                                   |
| RFC       | Request For Comment                              |
| RSSI      | Radio Signal Strength Indicator                  |
| SIFS      | Short Inter Frame Space                          |
| TCP       | Transmission Control Protocol                     |
| UOWN      | Underwater Optical Wireless Network              |
| VEN       | Vehicular Energy Networks                        |
| WANET     | Wireless Ad hoc Networks                         |
| WMN       | Wireless Mesh Networks                           |
| 5G        | Fifth Generation Cellular System                 |

generally a cross-layer task. However, we place each diversity option at the layer which performs its core part. At the lowest layer, PHY, the diversity is over the transmission channel and based on the fact that individual channels experience independent fading phenomena [15]. The independent channels are generated by 1) spreading the signal over a broader frequency band (frequency diversity), e.g., Direct Sequence-Code Division Multiple Access (DS-CDMA) [16], or carrying it on multiple frequency carriers, e.g., Orthogonal Frequency Division Multiplexing (OFDM) [17], 2) spreading the data over time (time diversity), and 3) providing multiple physical transmission paths per link (space diversity), e.g., Multiple-Input and Multiple-Output (MIMO) [18] and Space-Time Coding (STC) [19].

One layer up, at the DLL level, a data frame can be spread over multiple transmitted data frames through a technique traditionally called frame interleaving [20]. At the network level, i.e., NET, the content of a subject packet is transmitted by multiple carriers such as paths, packets, and nodes. The Multi-Path Routing (MPR), as opposed to the Alternate-Path Routing (APR) [21] in wired networks, sends a packet through multiple paths simultaneously (path diversity) to compensate for the unreliability of individual paths [22]. The Network Coding (NC) provides diversity by transmitting carefully designed mathematical combinations of multiple original packets instead. The mathematical combination can be implemented at the packet level [23] [24], and the symbol level [25]. Finally, the OR [26] takes advantage of the broadcasting nature of the wireless medium and makes all the overhearing nodes incrementally contribute to the forwarding process (node diversity).

It is worth mentioning that diversity options at the same layer or different layers can be combined to provide better resilience against the unreliability of wireless medium, for instance, the use of joint OR and intra-flow network coding at the NET layer in [27] and [23].

B. OR Description

Opportunistic routing is a highly capable scheme benefitting from the broadcast nature of the wireless medium, especially in, but not limited to, static and semi-static wireless environments. As well as its original application in WMNs and WSNs, OR has very recently found its place in the aforementioned emerging wireless applications, including the Smart City [28], VANET [29]–[31], IoT [32]–[34], D2D communications [35] [36], and cognitive wireless networks [37] [38].

OR forces a subset of nodes overhearing a batch of in-transit packets, to cooperatively participate in the forwarding process. In fact, OR relaxes the notion of the next hop in traditional wireless routing and replaces it with an ambitious scheme that opportunistically exploits all the potential forwarders (which are closer to the destination than the sender). In other words, OR provides the possibility of packet delivery over different paths. Therefore, the merit of OR lies in extending the forwarding role to the members of the forwarder list. In contrast to the single-path (multiple) routing, which specifies a single (multiple) path(s) for forwarding a packet, OR creates an ordered set of nodes wherein a node takes a forwarding action when its predecessors on the list fail to transmit.

In the following, the basics of OR are discussed for a better understanding. The main steps in a conventional OR protocol are:
In-advance calculation and dissemination of OR metric of all nodes for each source-destination pair,
- candidate forwarder set (CFS) formation,
- ordering of the CFS according to their OR metric values,
- forwarder list selection,
- members of the forwarder list becoming aware of their selection and location on the list,
- and transmission scheduling.

Figure 5 is a simplified illustration of the transmission co-selection scheme, and/or transmission scheduling protocols might differ in OR metric calculation, forwarder list their priorities as well. It is fair to say that different OR become aware of their forwarder list selection, they must know transmissions from the members of the forwarder list are contribute to forwarding the heard transmissions. The nodes The members of this list are the ones who can incrementally according to a criterion specific to the employed OR protocol, OR metric values. A subset of the ordered CFS is selected, green color nodes in Fig. 4) are ordered according to their forwarding merit for a specific source-destination transmission, the eligibility of the node to be placed on the CFS, i.e., its incremental contribution capability, might depend on the status of other potential contributors as well. Orange-color nodes in Fig. 4 demonstrates a related situation wherein they are prevented from consideration for forwarding, as they cannot offer more contribution than what is already provided by src.

Regarding the incremental contribution, a somewhat similar situation arises in the case of nodes located on correlated wireless paths. By assuming in-advance knowledge of all OR metric values, the members of the CFS (i.e., the light-green color nodes in Fig. 4) are ordered according to their OR metric values. A subset of the ordered CFS is selected, according to a criterion specific to the employed OR protocol, as the forwarder list (i.e., dark-green color nodes in Fig. 4). The members of this list are the ones who can incrementally contribute to forwarding the heard transmissions. The nodes on the forwarder list with lower metric values have higher priorities regarding the transmission cooperation. Since the transmissions from the members of the forwarder list are scheduled based on their priorities, not only should they become aware of their forwarder list selection, they must know their priorities as well. It is fair to say that different OR protocols might differ in OR metric calculation, forwarder list selection scheme, and/or transmission scheduling.

Figure [5] is a simplified illustration of the transmission co-operation in OR compared with the traditional routing in a wireless network. As the sample topology in the figure shows, the source and the destination nodes (src and dst) are not in direct reach of each other. The potential forwarding nodes A, B, and C, which can hear each other, all have error-free and erroneous links to dst and src (shown by thick and light solid lines), respectively. Moreover, node C has the worst link to src amongst the three, while the other two have equal link qualities. We assume that src intends to deliver five packets to dst.

The upper part of Fig. 5 shows the src→dst's packet delivery and channel business using the traditional best-path routing via node A. For the sake of simplicity, it is assumed that errorlessly-received packets at node A on the first attempt (i.e., the packets 1 and 3) are received successfully on the second attempt.

The lower part of Fig. 5 illustrates the delivery of packets using OR. Based on the perfect-second-hop links assumption, nodes A, B, and C have the same priorities in the context of OR. Thus, just due to implementation, we assign the highest and the lowest priorities to nodes A and C, respectively. The first time step in the figure shows that the packets queuing at src ready for transmission. The second time step shows the broadcast transmission of the packets by src. In the third time step, the different reception patterns at nodes A, B, and C, due to different link qualities, is illustrated. The fourth time step shows the scheduling concept and cooperative forwarding. The cooperative forwarding in OR reduces the channel contention in traditional MACs. It should be noticed that the time-aggregate transmissions by nodes A, B, and C, on the second hop, is the same as the transmissions on the first hop. For simplicity, it is implicitly assumed that the whole batch is collectively received by the intermediate nodes on the first attempt. Finally, the fifth time step demonstrates successful reception of data packets at dst.

The shorter fourth time step can observe the achievable OR saving, and in turn, shorter total channel business compared to the longer fourth time step in the traditional routing.

C. OR History

The exploitative manner of OR has proven to be successful in increasing the overall throughput seen by a single flow [39] [27]. There have been earlier non-OR, yet somewhat similar, attempts of limited and prioritized rebroadcasting according to some criteria (e.g., [40] introduces adaptive broadcast for reliable delivery of emergency warning packets in inter-vehicle communication as opposed to simple flooding). However, OR was first introduced through the EXOR protocol [39] [26]. Typically, OR uses the notion of the data batch instead of a single packet as the primary data unit to facilitate cooperation between forwarding nodes. Since this consideration intrinsically increases the data delivery delay, OR is a viable forwarding method for bandwidth-intensive multimedia applications with elastic delay requirements. A useful numerical example that shows the difference between OR and traditional routing protocols appears in appendix [VI].

The coordination between forwarding nodes, commonly known as scheduling, is a critical and challenging problem.
which was addressed in pioneer OR proposals \cite{39, 41--59} where the goal was to prevent duplicate packet transmissions. Alternatively, the seminal work of the MAC-independent opportunistic routing (MORE) \cite{27} protocol suggests the use of NC combined with the concept of distributively implemented transmission credits to eliminate the need for coordination between forwarding nodes. Network coding, best known for its ability to reduce the number of packet retransmissions, can substantially increase network throughput \cite{60}. MORE and its derivatives (e.g., \cite{61}) combine individual packets of the same batch using random network coding (i.e., intra-flow network coding). COPE \cite{62} is another successful method of integrating OR with inter-flow network coding. COPE reduces the number of transmissions by combining data packets from different OR flows. Several consequent OR proposals \cite{25, 63--71} mixed OR with NC in different ways following the footsteps of MORE and COPE.

\subsection*{D. OR Metric Design}

The varying characteristics of a wireless channel along with time, distance, environmental conditions, and interference/noise levels make the quality of links between a node and its neighbors unpredictable. Various routing metrics have been introduced to measure and fairly compare various path costs (as a precursor for applying any routing algorithm) \cite{72}. These metrics can accommodate several parameters, such as mobility, energy consumption, and QoS. As was pointed out earlier, in the context of OR, a metric is typically used to select and prioritize forwarding nodes from a set of candidate nodes and to set their level of cooperation. The performance of an OR protocol strongly depends on the selected forwarding nodes \cite{73, 74}. Therefore, the choice of a good and representative routing metric is of crucial importance to the overall network performance.

As Fig. 6 suggests, at its highest generality, a wireless routing problem starts with a given particular network type, for instance, a WSN. The specification of the network type carries the possible related sets of imposed constraints, available resources, and network features. The network features are usually of characteristic or capability nature, such as trust, mobility, or hardware, which are mostly specific to the network nodes and the wireless transmission channel. The constraints and resources are parameters usually of consumptive nature, such as bandwidth, time, or energy. Based on the constraints and the resources, a routing optimization problem is formed by selecting one or more performance measures (e.g., network lifetime), as the routing objectives, to be optimized. The solving process of this routing optimization problem results in a particular OR protocol, as well as a new OR metric if needed. The parameters present in the formulation of the resulting OR metric are usually the same as or derived from the items which appear in the features, resources/constraints, and objectives. The formulation of the OR metric is also very much dependent on the adopted optimization method, such as mathematical, learning-based, etc. The DSTT metric is a good representation of such a design process. Presented in the context of an Underwater Acoustic Wireless Sensor Network (UAWSN), the network features the particular water transmission channel and
the immobile sensor nodes with limited available energy as the primary constraint. DSTT and its related OR protocol try to heuristically optimize a combination of three OR objectives, the network's lifetime, the Packet Delivery Probability (PDP), and the geographical advancement per hop.

Regarding the OR metric design process, the following considerations should be taken into account:

- Not necessarily every OR metric goes through all the design steps of Fig. 6.
- Starting with a particular network type, the challenge of designing a good OR metric consists of choosing the set of right representative parameters (from the related network features, resources/constraints, and routing objectives), and establishing an appropriate relation (i.e., the OR metric’s formulation) between them using an optimization process. The resulting OR metric’s formulation is very much dependent on the choice of the optimization process.
- In particular platforms, for instance, CRNs, the OR metric design process might require extra considerations. The stochastic intermittent appearance and mobility (if applicable) of the primary and secondary users, make the availability of network resources such as time and frequency (i.e., spectrum) very fluid. In this situation, the OR metric design, and certainly its employing OR protocol, should address some extra challenges such as the spectrum availability, the interruption time, and the deafness problem (listening on the wrong channel) [75].

III. OR Metrics: A Survey

A. Motivation

It is generally understood that OR is an efficient diversity technique to combat the unreliability of the wireless medium, particularly in multi-hop scenarios. Looking at the related literature, newly emerged OR metrics [78]–[80], recently-devised opportunistic-based routing protocols [85], [87]–[98], extensive use of OR in new environments [4], networks [29] [5] and applications [79], and also the publication of recent OR surveys [99] [23] all point to the fact that OR and, certainly, OR metrics are still a very alive topic and of huge interest to wireless researchers. To justify the need for doing this survey, we proceed by summarizing the most relevant existing surveys in Table II. Table II briefly mentions the main contributions and limitations of each past work. [72] provides a formerly complete treatment of routing metrics rather than OR metrics. However, several of its provided traditional routing metrics have been employed in the context of OR later. [76] is a brief survey primarily on OR protocols. It considers a few OR metrics already introduced back then and classifies the OR protocols according to the hop-count nature of their underlying metrics. The third survey [75] gives limited coverage of OR metrics, due to its focus on a particular network type, the CRNs, with insufficient details. The most recent related surveys [77] [53] discuss the whole concept of OR and, of course, the OR metrics partially. Consequently, their contributions to OR metrics are lacking in detail and are non-exhaustive. Furthermore, they offer limited insight regarding related taxonomy and future research recommendations. There are other OR-related surveys in the literature (not mentioned in Table II) with little to no OR-metrics discussions. [99] and [23] explain a few OR metrics as part of their surveys on the joint OR and intra/inter-flow network coding in WMNs. [100] is a survey on just the mobility impacts on the OR algorithms, with no reference to OR metrics. It is worth mentioning an interesting survey on opportunistic routing, which should be distinguished from the conventional OR we are dealing with herein. The survey [101] proposes a framework for analyzing the routing algorithms in complex dynamic networks featuring a stochastic nature (e.g.,
strongly feel the need for a survey such as the one presented of the existing OR-metric review studies in the literature, we limitations, deficiencies, non-exhaustiveness, and outdatedness OR surveys do not provide a clear insight into the matter and notations and presentations (formulations). Cookbook-style encounter a large number of OR metrics with proprietary message advancing in OR.

sage advancing, as opposed to the opportunistic collaborative tent, occurrence of the communication opportunities for mes-

regards taking advantage of the casual, and possibly intermit-

time-variant random topology) due to the random behavior (e.g., mobility) of its nodes. However, the opportunism therein regards taking advantage of the casual, and possibly intermittent, occurrence of the communication opportunities for message advancing, as opposed to the opportunistic collaborative message advancing in OR.

Interested OR researchers studying the related literature encounter a large number of OR metrics with proprietary notations and presentations (formulations). Cookbook-style OR surveys do not provide a clear insight into the matter and do not satisfactorily fulfill research demands. Considering the limitations, deficiencies, non-exhaustiveness, and outdatedness of the existing OR-metric review studies in the literature, we strongly feel the need for a survey such as the one presented herein.

B. Contributions

In order to make this survey self-contained, a tutorial tailored to the structured approach of the survey is required. As such, the tutorial has been organized so as within which: a background on OR from a newly presented perspective, transmission diversity options across different layers of the communication protocol suite is provided; OR is described and compared with traditional routing in terms of performance improvement; a framework for OR metric design process is developed. Given the constantly-changing field of wireless, by adopting a structured, investigative, and comparative approach to OR metrics, we aim at keeping this tutorial survey relevant for as much longer as possible.

The main contributions of this tutorial survey are:

| Reference | Year | Contributions | Limitations |
|-----------|------|---------------|-------------|
| A Survey on Routing Metrics | 2007 | - The first survey on wireless routing. - Investigates the metrics using the following aspects, the influence factors, the mathematical properties, the design goal, the implementation characteristics, and the evaluation manner. - States the taxonomy for routing metrics based on their mathematical properties. - Provides a standard summary for each metric. | - Covers routing metrics rather than OR metrics. - The taxonomy gives minimal insight. - Lack of a comparative study. - No future direction recommendations. |
| Survey on Opportunistic Routing in Multihop | 2011 | - Reviews OR protocols. - Provides an OR-protocols categorization based on the hop-count nature of the underlying metric. | - Primarily on OR protocols. - Considers only a few OR metrics already available back then; now is very outdated. |
| Routing Metrics of Cognitive Radio Networks: A Survey | 2014 | - Discusses metric design challenges adequately; emphasizes on a cross-layer approach. - Provides the single-/multi-path metric categorization. - Simulation comparison between three metric subclasses. - Useful future research directions including hybrid metrics. | - Limited to CRNs. - Lack of formulation details on OR metrics. - An insightful taxonomy at the time of publication; now seems insufficient. |
| Opportunistic Routing in Wireless Networks: Models, Algorithms, and Classifications | 2015 | - Following a detailed discussion of OR, divides OR issues under three topics, OR metric, candidate (forwarder) selection, and candidate coordination (transmission scheduling). - Provides a taxonomy for each of these issues: local/end-to-end OR metric, control-based/data-based candidate coordination, topology-based/geographical-based candidate selection. - Some types of OR protocols are discussed. - Recommends some future directions on each OR issue, as well as on some, then emerging, scenarios involving mobility, multicasting, security, etc. | - Few OR metrics are mentioned. - More about OR protocols and candidate coordination/selection algorithms rather than OR metrics. - Incomplete OR metric categorization with limited insight. - Lack of comparative discussions/simulations. - Insufficient and unstructured OR metrics for future research directions. |
| A Survey on Opportunistic Routing in Wireless Communication Networks | 2015 | - Describes in detail the OR building blocks, CFS formation, OR metric calculation, forwarder list selection, and transmission scheduling, as well as their underlying techniques. - Categorizes OR approaches under five classes: geographic, link-state aware, probabilistic, optimization-based, and cross-layer. - Two easy-to-grasp quick references for OR protocols taxonomy and features. - Provides some OR future research directions. | - limited material about OR metrics with insufficient details. - The OR protocols taxonomy, though relevant, gives minimal perspective. - The quick reference of OR protocols’ taxonomy includes protocols that are not OR at all. - The future work recommendations comprise a mix of metric, protocol, and network type topics with no clear classification. |
A new representation of OR as a transmission diversity technique at the NET layer.
A new framework for the OR metric design process.

• A new taxonomy of OR metrics based on computation method and scope.
• Exhaustive coverage of OR metrics in the literature, and providing sufficient details for each metric, rather than merely listing them, which obviates interested OR researchers of frequent and unnecessary referring to the related original papers.
• Effort-intensive reformulation of OR metrics into a single unified-notation form (otherwise in differing proprietary notations) for better and easier understanding, without which any comparison between them is almost impossible.
• Drawing the evolution of metrics introduced by almost the same authors, and the interrelation between similar metrics introduced by different authors.
• Self-explanatory, easy-to-grasp, and visually-friendly quick references which can be used independently from the rest of the paper.
• Extensive simulations to compare the representatives of different OR metric categories in terms of network performance.
• A critical look to the fundamental points missed in the classic approach to OR metrics and the investigation of overlooked details in the definition of specific OR metrics.

• Comprehensive future research directions in line with the OR metric design process framework outlined earlier, which makes singling out research opportunities much more straightforward.

The inclusion of the tutorial part makes the paper self-contained, and beneficial to generalists as well as OR specialists. Moreover, the paper has been carefully organized and equipped with self-explanatory quick references, so that it can be referred to, not only in its entirety but selectively also.

C. OR Metrics: A Complete Classification Treatment

In this section, to provide perspective for interested researchers, we categorize OR metrics based on their two fundamental attributes, the computation scope, and the computation method. Then, in each category, the metrics are presented in chronological order, whereby it is interesting to follow how some later metrics evolved from earlier ones.

Classification Perspective: Routing metrics are used to prefer one routing solution to another. In traditional wired networks, divides routing metrics into two classes as local and global constraint metrics. The former includes the metrics defined over individual links (and possibly their immediate ingress/egress nodes). The latter includes the metrics defined over distinct paths calculated by combining each path’s constituent local constraint metrics using some link combination operators [6]. This classification falls short in providing a perspective in wireless OR networks (our main focus herein) since it does not consider the broadcast nature of wireless networks. In Figure 7, we present a taxonomy of OR metrics in terms of their computation methods and computation scopes. The computation scope of an OR metric determines the span of the network involved in calculating its value at a subject node. In a per-hop (local) metric, the span extends to those intermediate nodes (wirelessly reachable immediate neighbors), which can potentially help in relaying a flow towards a specific final destination. In other words, the information used to calculate the metric concerns only the joining link(s) between a node and a subset of its immediate neighbor(s) which can contribute, more than the node itself, to the delivery at the destination (see the lower part of Fig. 8). However, in an end-to-end OR metric, the metric’s computation scope spans until the final destination (see the upper part of Fig. 8). End-to-end OR metrics are calculated from the final destination back to the subject node in a recursive fashion. It is well understood that, compared to their per-hop counterparts, the end-to-end metrics feature higher accuracy, higher computational and information dissemination costs, and higher susceptibility to network changes. Regarding the latter, it should be noted that any topology changes beyond the next hop, excluding the destination (which undoubtedly changes the whole routing problem), will impact the related end-to-end, and not the per-hop, OR metric.

The computation method of an OR metric determines how many paths contribute to the metric’s calculation. In single-path metrics, the value of the metric determines the merit of the best path (as in a unicast transmission) from a subject node to the destination (see the upper-right part of Fig. 8). However, a multi-path metric considers the contribution of many loop-free paths [47] by taking advantage of the broadcast nature of wireless transmission (see the left part of Fig. 8). In fact, multi-path OR metrics are opportunistic as is OR itself. While locality and globality concepts in routing protocols and in routing metrics are consistent, it is essential to distinguish between the concept of single-/multi-path in routing protocols and in routing metrics. The single-/multi-path concept in routing protocols regards implementing the transmission policy through a single (multiple) path(s) which has (have) been previously ranked by their embedded routing metrics. The embedded routing metrics can be single-/multi-path regardless of the transmission policy choice of the corresponding routing protocol.

Figure 9 illustrates how the complete set of OR metrics, to be explained shortly, is divided among the four categories above. Grouping together of OR metrics with high similarities or common roots facilitates metric searching in the literature.

One of the confusing facts about the OR metrics is the numeroseness of the notations used, making any comparison between them almost impossible. For the sake of presentation
consistency, we introduce a unified notation, herein, and reface, as much as possible, the original formulations of the OR metrics accordingly. The unified notation makes extracting similarity/non-similarity patterns between different OR metrics an easier task.

Before proceeding with the OR metric explanations, the definition of some basic terms in the unified notation is presented.

**Definitions:** A simple common topology in OR is illustrated in Fig. 10. Let src, dst and Cᵢ be the source node, destination node and candidate forwarder set for an intermediate node i. The nodes in Cᵢ can potentially help node i in delivering data packets from src to dst (since they are wirelessly reachable by i and have better relevant metric values than that of src). We assume that the members of Cᵢ are sorted according to their respective priorities defined by their corresponding OR metrics (in which lower index shows a higher priority). The transmission by a higher-priority node prevents lower-priority nodes from transmitting. In OR, a subset of Cᵢ is selected as the set of participating members to realize an opportunistic route between src and dst at level i. We denote this subset by Fᵢ, i.e., node i’s forwarder list. The goal of each OR protocol is to find Fᵢ at each routing level i to maximize the overall throughput of the selected opportunistic routes.

In the definition of OR metrics, three important delivery probabilities appear frequently, which will be explained shortly.

The link quality from node i to node j is commonly measured by the packet delivery probability, pᵢj. For example, pᵢj = 0.7 means that on the average, 7 of 10 data packets transmitted by node i are received by node j. This parameter is key to the definition of almost all OR metrics. Therefore, the parameter is detailed in section III-C. While not always true, in the literature, links are usually considered to be symmetrical, which means that pᵢj = pⱼi. Many other important parameters are also derived from this parameter.

Pᵢ is defined as the probability that at least one member of Fᵢ successfully receives the packet transmitted by node i:

\[ Pᵢ = 1 - \prod_{j \in Fᵢ} (1 - pᵢj) \]  \hspace{1cm} (1)

P(i,k) is the probability that the k-th candidate (or forwarding) node receives the transmitted packet from node i while all other higher-priority nodes fail to receive the packet:

\[ P(i,k) = pᵢk \prod_{j=1}^{k-1} (1 - pᵢj) \]  \hspace{1cm} (2)

In eq. (1), the nodes in the forwarder list are assumed to be descendingly indexed in terms of priority. Pᵢ, is the opportunistic reception probability when the sender is i and the receivers are members of Fᵢ. P(i,k) is the opportunistic reception probability for the sender i and a single opportunistic receiver (i.e., k).

For ease of reference, Table III lists the most common notations appearing in the definition of OR metrics along with their descriptions.

Figure 9 illustrates the four classes of different computation scope/computation method combinations.

1) Single-Path/End-to-End OR Metrics: In this class, metrics are calculated recursively along a single path (best path) from the destination backward. The following relevant metrics are presented in chronological order.

- **Expected Transmission Count (ETX)**: The ETX of a link is defined as the average number of packet transmissions required to deliver a packet over the link successfully. ETX is calculated using the forward and reverse delivery ratios of the link. If the forward and reverse delivery ratios of a link are pᵢⱼ and pⱼᵢ, respectively, the ETX is:

  \[ ETX(i,j) = \frac{1}{pᵢⱼ \cdot pⱼᵢ} \]  \hspace{1cm} (3)

The forward delivery ratio, pᵢⱼ, accounts for the successful delivery of the subject packet, and the reverse delivery ratio, pⱼᵢ, accounts for the successful delivery of the corresponding acknowledgment. The ETX of a route is calculated as the sum of its links’ ETXs. A sample proposal for distributing ETX information among network nodes is to use a designated node. Suppose that

![Fig. 7: Taxonomy of OR metrics.](image-url)
Fig. 8: Visualization of OR metrics classifications according to their computation methods and scopes.

Fig. 9: Categorization of OR metrics according to their computation methods and scopes, and also bundled based on high similarity or common root.

Each node has calculated the ETX metric for all the links between itself and its immediate neighbors. Then, the node sends this information throughout the network. After receiving all the one-hop ETXs, the designated node can calculate the ETX of the path between any two nodes (any potential source-destination pair) and distribute them across the network upon request.

Clearly, the ETX metric is entirely different from the hop count metric, which does not account for link quality.

- **modified ETX (mETX), Effective Number of Transmissions (ENT) [105]**: As discussed previously, the ETX implicitly presumes i.i.d. bit errors in a single packet transmission and also in successive packet transmissions. mETX relaxes this assumption by considering the variability of the channel at the packet timescale and its probable subsequent retransmissions. mETX is defined as:

\[
mETX = \exp(E[\Sigma] + \frac{1}{2} Var[\Sigma])
\]

where \( \Sigma \) is the logarithm of the required number of transmissions over a link, the first term in the exponent on the right represents the average level of channel bit error probability over long periods of time, and the second term in the exponent accounts for the packet-to-packet variability of the bit error probability. From eq. (4), it is obvious that \( mETX \geq ETX \). Similar to the ETX metric, mETX of a path is equal to the summation of its constituent links’ mETXs.
TABLE III: Unified notations

| Notation | Description | Variants/Note |
|----------|-------------|---------------|
| i,j,h/ src/dst | General node/Source node/Destination node |  |
| C_i/F_i | Candidate forwarder set/Forwarder list for node i |  |
| c | Cost |  |
| B | Bandwidth |  |
| E | Energy |  |
| R | Communication range |  |
| i,k | Geographical advancement |  |
| T_{trust}/ST | Trust/Social Tie |  |
| L | Total delay or time/Partial delay or time |  |
| P(i,j) | Packet size |  |
| r | Transmission rate |  |
| p_{i,j} | Packet deliver probability from node i to node j |  |
| P_{F_i} | Probability that at least one member of F_i receives node i's packet |  |
| P(i,k) | Probability that the k-th candidate is the first in F_i to receive node i's packet |  |

Fig. 10: Sender src communicates with destination dst. Node i is an active forwarding node on behalf of src. C_i is a list of next-hop candidate nodes, i.e., candidate forwarder set, for node i. Node i selects a sublist of these nodes F_i as the next-hop forwarding nodes, called forwarder list.

ENT attempts to improve the aggregate throughput by limiting the number of link-layer retransmissions and, if needed, allowing higher layers to handle correct receptions. ENT is defined as:

\[ ENT = \exp(E[\Sigma] + 2\delta Var[\Sigma]) \]  

(5)

ENT is very similar to mETX with the difference of an extra degree of freedom \( \delta \), which is related to the maximum number of allowed link-layer retransmissions.

- **Markovian metric (M-Markov)** \([106] \): Conventional routing metrics generally consider independent links. The M-Markov metric \([106] \), which is more of a concept rather than a concrete metric, introduces some context information into the link cost modeling. This metric calculates the cost of a path connecting node i to dst as the summation of the constituent links’ costs, each conditioned on its previous links cost:

\[ c(i,dst) = c(i,i+1) + \sum_{j=i+1}^{dst-1} c(j \rightarrow j+1|j-1 \rightarrow j) \]  

(6)

\[ \text{Cost} = c = c_{\text{cons}}, c_{\text{rec}}, c_{\text{sys}} \]

\[ B_{\text{new}}, B_{\text{new}}, B_{\text{dest}}, B_{\text{loc}} \]

\[ E_{\text{new}}, E_{\text{tot}}, E_{\text{res}}, E_{\text{rec}}, E_{\text{track}}, E_{\text{sink}}, E_{\text{cons}} \]

1The abbreviation is from the authors of this survey for better reference.

Considering independent links makes the conventional routing metrics as special cases of the M-Markov metric.

- **Opportunistic Link Transmission (OLT)** \([107] \): OLT defines a multi-hop and single-path metric in slotted Cognitive Radio (CR) networks by considering transmission, queuing, and access and by excluding processing and propagation delays:

\[ OLT^{(N)} = \sum_{i=0}^{N} \frac{1}{\mu_i - \lambda_i} \]  

(7)

where \( \mu_i \) and \( \lambda_i \) denote the processing and arrival rates at node i. Thereafter, node i’s merit for forwarding a packet is measured by:

\[ \min_{i\in M_i} \{OLT_i, (OLT_i^{(2)}, \ldots, OLT_i^{(N)}) \} \]  

(8)

where \( N \) is equal to the maximum number of hops over all opportunistic paths from node i to the destination, and \( M_i \) denotes the number of N-hop opportunistic paths from node i to the destination.

- **Energy Shortage Cost (ESC)** \([108] \): ESC concerns mobile WSNs, where sensing nodes occasionally meet sinks. If sinks are encountered frequently, nodes will transmit their data directly to them. Otherwise, the transmissions are done through other forwarding nodes with better links to the sinks. ESC is defined by:

\[ ESC(i, sink_i) = \frac{E_{\text{cons}}(i, sink_i)}{E_{\text{res}}} \]  

(9)

where \( E_{\text{cons}}(i, sink_i) \) represents the energy required by node i to deliver a packet (message) to its corresponding sink, sink_i. \( E_{\text{cons}}(i, sink_i) \) is inversely proportional to the delivery probability towards sink_i, and \( E_{\text{res}} \), is the remaining energy of node i. Although the scope of the metric appears to be end-to-end, the details of the computation method are unmentioned and unclear in the paper.

- **Metric of the Opportunistic Routing Admission Control protocol (M-ORAC)** \([109] \):

2The abbreviation is from the authors of this survey for better reference.
M-ORAC is an admission-based OR scheme that prunes candidates that are not able to fulfill the bandwidth and energy requirements of a new flow. A forwarding node $i$ admits a new flow that satisfies the following conditions:

$$
\begin{align*}
\rho_{B_i} &= \frac{B_{cur} + B_{new}}{B_{tot}} < 1, \\
\rho_{E_i} &= \frac{E_{rem} + E_{new}}{E_{tot}} < 1
\end{align*}
$$

(10)

where $\rho_{B_i}/\rho_{E_i}$ is the bandwidth/energy measure index, $B_{cur}/B_{new}$ shows the bandwidth requirement of the accepted flows/new flow, and $E_{rem}/E_{new}$ denotes rough estimation of the energy consumption of the accepted flows/new flow. Finally, $B_{tot}$ and $E_{tot}$ represent the bandwidth of node $i$ to service incoming traffic flows and total energy budget of node $i$, respectively. After finding eligible candidates, a new metric, called M-ORAC, is used for prioritization. M-ORAC is defined as follows:

$$
\text{M-ORAC}(i, dst) = \alpha \rho_{B_i} + \beta \rho_{E_i} + \gamma \text{ETX}(i, dst) + \varphi \frac{d(src, dst) - d(i, dst)}{d(src, dst)}.
$$

(11)

Clearly, M-ORAC makes a trade-off between the congestion control, routing quality, and energy consumption by applying the corresponding coefficients $\alpha$, $\beta$, $\gamma$, and $\varphi$.

- **M-SNR**: The cost metric $c(i, dst)$ represents the SNR-related cost from node $i$ to the destination $dst$. For node $i$, this cost is updated according to the information in the header of the received update messages flooded over the network as follows:

$$
\begin{align*}
c(i, dst) &= \begin{cases} 
c(i + 1, dst) + 1 & ; SNR_{dst} > SNR_{THSLD} \\
    c(i + 1, dst) + 1 & ; SNR_{THSLD} + 1 - SNR_{dst} = 0 \\
    c(i + 1, dst) + 1 & ; SNR_{THSLD} + 1 - SNR_{dst} < 0 \\
\end{cases}
\end{align*}
$$

(12)

where $SNR_{dst}$ and $SNR_{THSLD}$ are the SNR of the signal from $dst$ at the node right after node $i$, i.e., node $i+1$, and a threshold representing the maximum observed SNR in practical Mobile Adhoc NETworks (MANET) environments, respectively. By this cost-update policy, higher packet forwarding probability is given to a node with high-SNR links to the destination.

The definition of $SNR_{THSLD}$ in [110] requires clarification since it seemingly makes the first condition in eq. (12) irrelevant.

- **Q-ETX** [38]: This metric considers the backlog transmission queue of a relay node as well as its ETX and is defined as:

$$
\text{Q-ETX}(i, dst) = \alpha Q(i) + (1 - \alpha) \text{ETX}(i, dst),
$$

(13)

where $Q(i)$ denotes the transmission queue length at node $i$. Since this metric is defined in the context of slotted CRNs, both $Q$ and ETX are calculated on the condition of channel availability and for the limited duration of a single time slot.

Note: The single-path/end-to-end OR metrics are not, by their very nature, opportunistic, since they do not benefit from the broadcast nature of the wireless medium. These metrics can be equally embedded in traditional and opportunistic routing protocols; for instance, ETX was initially introduced in the pre-OR era. However, their extensive use in OR protocols label them as important OR metrics.

2) **Multi-Path/End-to-End OR Metrics**: As these are end-to-end metrics, they are calculated recursively along multiple paths from the destination backward. We intuitively expect this class of metrics, which employs more wireless path opportunities, to be more inclusive than its single-path counterpart. The relevant metrics are described in chronological order.

- **Expected Any-path transmissions (EAX)** [111], [112]:

  ETX ignores the broadcast nature of wireless media, and can only predict the behavior of the individual links that belong to a particular opportunistic path. However, OR aims to benefit from the broadcast nature of WNs to enhance network throughput. EAX was introduced to achieve greater consistency between OR and its employed cost metric.

  As a pioneering opportunistic metric, EAX computes the transmission cost of each opportunistic path recursively to find the best opportunistic path. The $EAX(i, dst)$ metric is defined as the expected number of transmissions that $i$ should make for the successful delivery of the transmitted data packet at $dst$:

$$
EAX(i, dst) = \frac{1 + \sum_{j \in F_i} P(i, j) EAX(j, dst)}{P_{F_i}}.
$$

(14)

Note that in eq. (14), the numerator is the expected number of transmission attempts that $i$ and the members of $F_i$ must make for the successful delivery of the data packet at $dst$ (‘1’ corresponds to the $i$’s attempt and the summation corresponds to the number of attempts made by the members of $F_i$). The denominator is the probability that at least one member of $F_i$ receives the packet transmitted by $i$. $P(i, j) EAX(j, dst)$ is the EAX cost of node $j$ given that it acts as a forwarding node. EAX is a multiple-hop, symmetric, and multi-path metric that considered the anypath forwarding scheme for the first time. Among the many works that have adopted EAX as their main metric are [47], [74], [113], and [114].

- **EOTX** [115]: EOTX, the multi-path generalization of ETX, computes the minimum expected number of transmissions needed to deliver a packet from a sender to the destination using all the available paths:

$$
\text{EOTX}(i, dst) = \min_{i \in \text{set}} \sum_{j \in F_i} P_{F_i} \text{EAX}(j, dst).
$$

(15)

where $P_{F_i}$ denotes the probability that all nodes in set $F_i$ receive a packet broadcast by node $i$ (therefore, it is different from $P_{F_i}$, which represents the probability of at least one node in $F_i$ receiving the packet). This metric resembles $z(i, dst)$ in eq. (17), which is used for the credit calculation of the forwarding nodes in the MORE routing protocol [27].
**Expected Any-path Communication Time (ExACT)** [116]: ExACT is a recursively defined metric that minimizes the total transmission time at the specified bit rate \( r \). ExACT starts from \( dst \) and finds the minimum ExACT value for the previous 1-hop candidates set and determines their ideal transmission rate, \( r^* \). This procedure is performed recursively until reaching node \( i \).

\[
\text{ExACT}(i, dst, r) = \frac{1}{r} \sum_{j \in F_i} P(i,j) \text{ExACT}(j, dst, r^*_j) + \frac{L}{P_{F_i}}.
\] (16)

In eq. (16), \( \frac{1}{r} \) represents a single packet’s transmission time. The correct formulation should use \( \frac{L}{r} \) to account for the packet length (for instance, see eq. (18) for EATT). In eq. (16), the use of \( r^* \) instead of \( r \) in \( \text{ExACT}(j, dst, r^*_j) \) emphasizes the different bit rates of the links.

**Expected Medium Time (EMT)**: EMT [117] is another recursive opportunistic metric that shares several similarities with other opportunistic metrics such as EAX [111]. EATT [118] and ExACT [116]. EMT models the expected transmission time from node \( i \) to \( dst \) as follows:

\[
\text{EMT}(i, dst) = \sum_{j \in F_i} P(i,j) \text{EMT}(j, dst) + \frac{L}{P_{F_i}}.
\] (17)

The lack of an additive term like the one in similar metrics above, which accounts for the source’s transmission, needs further verification.

**Expected Any-path Transmission Time (EATT)** [118], [119]: EATT, which is very similar to ExACT, selects an appropriate flow rate to simultaneously maximize network throughput and minimize transmission time. EATT is defined as follows:

\[
\text{EATT}(i, dst, r) = \frac{L}{r} \sum_{j \in F_i} P(i,j) \text{EATT}(j, dst, r^*_j) + \frac{L}{P_{F_i}}.
\] (18)

where \( L \) is the packet length, and \( r \) is the bit rate. \( r \) is selected to minimize \( \text{EATT}(i, dst, r) \).

**Opportunistic routing Residual Expected Network Utilities (OpRENU)**: The OpRENU [46], [120], [77] metric is designed for a utility-based routing paradigm where a positive value rewards the successful routing of a data packet after reducing the transmission cost. OpRENU is defined recursively with the same features of STR except for the addition of the transmission cost \( c \):

\[
\text{OpRENU}(i, dst) = \sum_{j \in F_i} P(i,j) \text{OpRENU}(j, dst) - c.
\] (19)

**Successful Transmission Rate (STR)** [121]: STR is another recursively defined metric that computes the successful transmission rate for every candidate node. The calculation of STR for an immediate neighbor of \( dst \) is straightforward: it equals the available transmission rate of the link between that neighbor and \( dst \). For other candidate nodes, the following formula is used:

\[
\text{STR}(i, dst) = p_{i1} \text{STR}(i, dst) + \sum_{j \in F_i} P(i,j) \text{STR}(j, dst).
\] (20)

The first term accounts for the transmission contribution of the highest-priority candidate, and the second term accounts for the other candidates’ contributions.

**Opportunistic End-to-end Cost (OEC)** [122], [123]: OEC reflects the energy cost of using an opportunistic path and is defined as follows:

\[
\text{OEC}(i, dst) = \frac{E_{\text{cons-TX}} + \sum_{j \in F_i} E_{\text{cons-RX}}}{P_{F_i}} + \sum_{j \in F_i} P(i,j) \text{OEC}(j, dst) .
\] (21)

where \( E_{\text{cons-TX}} \) is the remaining energy level of a node, and \( E_{\text{cons-RX}} \) is the consumed transmission/reception energy of a wireless node. Therefore, the first term in the numerator denotes the energy efficiency of the sender when sending a packet to \( F_i \). The second term in the numerator represents the energy efficiency of the members of \( F_i \) when receiving the transmitted packet.

**Expected number of Duty-Cycled wake-ups (EDC)** [124], [125]: The main goal of EDC is to minimize the node wake-up interval in WSNs. The lower the total duration of the wake-up intervals of a node is, the lower its energy consumption. Clearly, node \( i \) has two main concerns when selecting \( F_i \) members. First, node \( i \) should deliver the packet to at least one member of \( F_i \), which implies that the cardinality of \( F_i \) (i.e., \(|F_i|\)) should be increased. Second, the overall progress of the packet toward the destination (\( dst \)) should be maximized. If the selected \( F_i \) members are not optimal, the overall progress is deteriorated. In other words, from an overall progress perspective, high-quality forwarding members are favored. Hence, EDC should restrict the number of forwarding members. EDC attempts to make a fair trade-off between these two contradicting requirements as follows:

\[
\text{EDC}(i, dst) = \frac{1}{\sum_{j \in F_i} p_{ij}} + \sum_{j \in F_i} \frac{p_{ij} \text{EDC}(j, dst)}{\sum_{j \in F_i} p_{ij}}.
\] (22)

The first part of eq. (22) is a rough estimation of the number of transmission attempts by node \( i \) to deliver a packet to a member of \( F_i \). In this formulation, the order of \( F_i \) members and their wake-up status are ignored. In the second part of the equation, the required wake-up duration of each \( F_i \) member, in time interval \( T \), for the successful delivery of the packet at \( dst \) is roughly estimated by computing the expected EDC values over all members of \( F_i \). The first part of the equation improves
with $|F_i|$ while the second part improves with the quality of the selected forwarding nodes. Minimizing the EDC metric reduces energy consumption. Note that each node will resend an undelivered data packet until a forwarding node has acknowledged it.

**Expected Transmission Cost (ETC), Expected Available Bandwidth (EAB), Bandwidth-Cost Ratio (BCR): BCR** [50], [126] is proposed to estimate the available bandwidth while considering the expected transmission cost (ETC) for an opportunistic flow. ETC is defined in the same way as EAX:

$$ETC(i, dst) = \frac{1 + \sum_{j \in C_i} P(i, j) ETC(j, dst)}{P_{C_i}} \tag{23}$$

ETC considers the cost from node $i$ to $C_i$ and the cost from $C_i$ to $dst$ as usual. Then, the expected available bandwidth (EAB) for node $i$ is defined as:

$$EAB(i) = \min\{B_{loc}(i), B_{opp}(i)\} \tag{24}$$

where $B_{loc}(i)$ and $B_{opp}(i)$ are the local and opportunistic available bandwidths of node $i$, respectively. The channel capacity, channel idle time, packet length, average back-off time, SIFS, DIFS and the time required for sending an ACK packet must be considered to obtain an accurate estimation of $B_{loc}(i)$. $B_{opp}(i)$ is estimated in the same manner as ETC:

$$B_{opp}(i) = \frac{\sum_{j \in C_i} P(i, j) EAB(j)}{P_{C_i}} \tag{25}$$

$B_{loc}(i)$ is not required in the definition of $B_{opp}(i)$ since we have considered its effect in eq. (24). Finally, the BCR metric is defined as the ratio of ETC to EAB.

**Correlation-aware EAX (cEAX):** Link correlation is caused by (i) cross-network interference under a shared medium and (ii) correlated fading introduced by highly dynamic environments. This phenomenon leads to correlated packet receptions among receivers that are closely located and might result in suboptimal forwarder selection, thereby reducing network performance. Wang et al. [127]–[131] studied the effect of link correlation on the performance of OR and proposed the correlation-aware EAX (cEAX) metric, which is defined in a same way as EAX:

$$cEAX(i, dst) = \frac{1 + \sum_{j \in F_i} JP{PR}(i, j) cEAX(j, dst)}{1 - JP{LS}(F_i)} \tag{26}$$

where $JP{PR}$ and $JP{LS}$ stand for the joint packet reception and joint packet loss probabilities, respectively. $JP{PR}(i, j)$ represents the probability that $j$ receives the packet transmitted by node $i$ when higher-priority forwarding nodes fail to do so in the presence of link correlations. $(1 - JP{LS}(F_i))$ means that at least one member of $F_i$ has successfully received the transmitted packet.

**Multi-channel Expected Anypath Transmission Time (MEATT):** MEATT [132] is an opportunistic metric that extends the ETT metric for multi-channel multi-radio mesh networks in the same manner as EAT. MEATT is designed so that the proper channel is implicitly selected by the current forwarder when estimating the expected anypath transmission time. MEATT attempts to minimize the expected transmission time by searching available channels ($K_i$) for a proper channel number at each forwarding node, as follows:

$$MEATT(i, dst) = \arg \min_{k \in K_i} \frac{L}{r_k} + \sum_{j \in F_i} \alpha_j P(i, j, k) MEATT(j, dst, k) \quad (27)$$

In eq. (27), $L$ is the packet length, $r_k$ is the bit rate in channel $k$, $\alpha_j$ is a tunable parameter to account for channel diversity. $P(i, j, k)$ and $P_F(k)$ have the same meaning as before, except for the inclusion of channel $k$.

**Expected Anypath Delay (EAD) [133]:** The EAD metric is proposed for establishing a minimum-delay OR route for an opportunistic flow in a multi-channel scenario. The data delivery delay comprises both the transmission time ($T_{TX}$) and the stall time ($T_{stl}$) resulting from intra-flow interference. EAD uses the path established by the EAX [111] metric as its primary path and estimates the data delivery delay as follows:

$$EAD(i, dst) = T_{stl, i} + T_{TX} = \sum_{j \in path(i, dst)} (T_{stl} + T_{TX}) \tag{28}$$

In eq. (28), the summation is over the set of nodes on the EAX path between node $i$ and $dst$, and $T_{TXj}$ is the required transmission time for node $j$. When two direct neighbors attempt to use the same wireless channel simultaneously, EAD prioritizes the neighbor that has a shorter transmission time. Therefore, the stall time of node $j$ ($T_{stl,j}$) can be estimated as the minimum transmission time among node $j$ and its direct neighbors on the $i$ to $dst$ path. EAD estimates $T_{TXj}$ in the same manner as other opportunistic metrics with minor differences. EAD first defines $N(j \to F_j)$ as the average number of packet transmission attempts by node $j$ toward $F_j$ to deliver a data packet from $j$ to $dst$:

$$N(j \to F_j) = \sum_{j \in F_h} \frac{N(h \to F_h)}{P_{F_h}} P(h, j) \tag{29}$$

In eq. (29), $N(h \to F_h)$ is the expected number of packets node $h$ should send to successfully deliver a data packet to its forwarder list $F_h$. We can estimate $T_{TXj}$ by multiplying the time required for transmitting a single data packet $L/r$ and the expected number of transmissions node $j$ should make:

$$t_{TXj} = \frac{N(j \to F_j) L}{r} \quad \tag{30}$$

**Expected Weight of Anypath Transmissions (EWATX) [134] [135]:** EWATX introduces a multi-form (but not
multi-dimensional) anypath OR metric that can consider different quality parameters one at a time:

\[
EWATX_k(i,dst) = \frac{w_k(i) + \sum_{j \in F_i} P(i,j)EWATX_k(j,dst)}{P_{F_i} }; \quad 1 \leq k \leq K .
\]  

(31)

\( EWATX_k(i,dst) \) in eq. (31) represents the weighed average of the anypath weights from node \( i \) to the destination through a forwarder list \( F_i \), \( w_k(i) \) is the \( k \)-th quality parameter value of node \( i \), and \( K \) is the number of different quality parameters to be considered. For instance, when \( K = 1 \), \( w_1(i) \) may represent the average time required for node \( i \) to complete one transmission. When \( K = 2 \), \( w_1(i) \) may be as above, and \( w_2(i) \) may represent the energy consumed by node \( i \) to complete one transmission. This metric is very similar to the EAT metric.

- **Metric of the Long Lifetime Any-path protocol (M-LLA)** [31]: M-LLA is a dynamic opportunistic metric that addresses the link stability issues in VANETs. First, M-LLA estimates the stability of a dynamic wireless link established between two moving vehicles. Then, the best opportunistic path between \( src \) and \( dst \) is found using the M-LLA metric. Assume that two vehicles (\( i \) and \( j \)) are connected by a wireless link at time \( t_0 \) and that the distance between them is denoted by \( d_{ij}(t_0) \). Assume also that these vehicles remain connected after \( \Delta t \) if the distance between them \( (d_{ij}(t_0 + \Delta t)) \) does not exceed \( R \), i.e., the wireless coverage range. We can decompose \( d_{ij}(t_0 + \Delta t) \) into \( d_{ij}(t_0) + \Delta d_{ij} \), where \( \Delta d_{ij} \) is the relative increase in the geographical advancement between node \( i \) and node \( j \). The stability index is defined as:

\[
s_{ij} = 1 - \frac{\min(\Delta d_{ij}, R)}{R} .
\]  

(32)

The best value of \( s_{ij} \) is 1. This value is assigned to the link when both vehicles have equal relative movement vectors. The worst value of \( s_{ij} \) is 0. This value is assigned to the link when the distance between two nodes exceeds \( R \) (communication range) in a time period \( \Delta t \). We can modify the link cost definition to include the stability index as follows:

\[
c_{ij} = \frac{1}{p_{ij}s_{ij}} .
\]  

(33)

The opportunistic cost between node \( i \) and \( dst \) is defined as:

\[
M-LLA(i,dst) = M-LLA(i,F_i) + M-LLA(F_i,dst) ,
\]  

(34)

where \( M-LLA(i,F_i) \) is the cost of delivering a packet from node \( i \) to at least one member of \( F_i \), and \( M-LLA(F_i,dst) \) is the opportunistic path cost from \( F_i \) to \( dst \). M-LLA is derived as follows:

\[
M-LLA(i,dst) = \frac{1}{1 - \prod_{j \in F_i} (1 - p_{ij}s_{ij})} + \sum_{j \in F_i} \frac{p_{ij}s_{ij}M-LLA(j,dst) \prod_{k=1}^{j-1} (1 - p_{ik}s_{ik})}{1 - \prod_{j \in F_i} (1 - p_{ij}s_{ij})} .
\]  

(35)

or equivalently:

\[
M-LLA(i,dst) = \frac{i\sum_{j \in F_i} M-LLA(j,dst)p_{ij}s_{ij} \prod_{k=1}^{j-1} (1 - p_{ik}s_{ik})}{1 - \prod_{j \in F_i} (1 - p_{ij}s_{ij})} .
\]  

(36)

The only difference between eq. (34) and its counterpart in [118], [119] is the inclusion of a stability index. Additionally, eqs. (36) and (14) are closely related. Being similar to EAX, except for the inclusion of the node speed and stability index, M-LLA has an identical feature set.

- **Opportunistic Energy Cost with Sleep-wake schedules (OECS)** [136]: The OECS metric reflects the energy cost of an opportunistic path:

\[
OECS(i,dst) = \frac{E_{\text{req}} + E_{\text{dr}} + E_{\text{trans-TX}}}{P_{F_i}} + \frac{\sum_{j \in F_i} P(i,j)OECS(j,dst)}{P_{F_i}} .
\]  

(37)

OECS and OEC are similar except that the former models the required energies for broadcasting and receiving beacons.

- **Expected Transmission Cost (ETC)** [137], [138]: This metric is proposed in heterogeneous duty-cycled WSNs. In duty-cycled networks, the transmission cost associated with finding at least one awake forwarding node is called the rendezvous cost, \( c_{rv} \). This cost is stated to be proportional to the wake-up ratio of all the forwarding nodes. The total cost of node \( i \) sending a packet over a single hop is then:

\[
ETC^*(i,F_i) = \frac{c_{ij} + c_{com}}{T_{cycle}} ,
\]  

(38)

where \( c_{com} \) and \( T_{cycle} \) are the packet transmission cost and cycle duration, respectively. Thereafter, the expected multi-hop transmission cost or metric is calculated as:

\[
ETC^*(i,dst) = ETC^*(i,F_i) + \sum_{j \in F_i} \frac{ETC^*(j,dst)}{|F_i|} .
\]  

(39)

The * superscript is intended for distinction with the ETC metric in eq. (23).
between node \( i \) and \( dst \) consists of \((dst-i+1)\) nodes, then, we define:
\[
c(i, dst) = (dst-i) \prod_{j=i}^{dst-1} p_{j+1} + c(i, dst-1)(1-p_{dst-1, dst}).
\] (40)

The first term on the RHS of eq. (40) is the success probability of successive transmissions from node \( i \) to \( dst \). The second term on the RHS represents the cost of a situation where \( dst-1 \) fails to deliver the packet to \( dst \).

ETCoP is then defined as:
\[
ETCoP(i, dst) = \frac{c(i, dst)}{\prod_{j=i}^{dst-1} p_{j+1}(i, dst)}. \quad (41)
\]

ETCoP prefers a path whose link component’s quality gradually increases towards the destination.

- **Expected Energy Consumed Along the Path (EEP)** [140]:

EEP was originally introduced as an anycast routing metric and was used by EDAD [141], an energy-centric cross-layer data collection protocol designed for anycast communications in asynchronously duty-cycled WSNs, and not in the context of OR. EEP was later used as an OR metric by [140] for opportunistic many-to-many multicasting in duty-cycled WSNs. \( EEP_i \) denotes the expected energy required to deliver a packet from node \( i \) to the destination and is defined as:

\[
EEP(i, dst) = \frac{\sum_{F \in F_i} EEP(j, dst) + 2}{|F_i|} + \frac{T_c}{T_F} \quad (42)
\]

The first part of the RHS in eq. (42) is an average of the energies required by each member of \( F_i \) for delivery to the destination (the first term of the summation), plus the energy consumed for the packet transaction between node \( i \) and node \( j \) (the second term of the summation). The second part of the RHS in eq. (42) accounts for the average energy consumed until one member of the CFS wakes up to respond, as the network is duty-cycled. \( T_c \) and \( T_F \) are the average sleep time of each node and the time duration of each data frame transmission, respectively.

- **Expected End-to-end Latency (EEL)** [142]: EEL is proposed for Underwater Wireless Sensor Networks (UWSN). The goal of EEL is to maximize goodput. \( EEL(i, dst) \) is defined as the constrained end-to-end delay from node \( i \) to \( dst \):

\[
EEL(i, dst) = \frac{T_{MAC_F_i} + T_{Crd_F_i}}{P_{F_i}} + \sum_{jk,F_i} P(i,j)EEL(j, dst) \quad (43)
\]

\( EEL(i, dst) \) must be lower than a threshold. The parameter \( T_{MAC_F_i} \) is composed of four parts, the MAC contention time, the packet transmission delay, the propagation delay, and the ACK delay. \( T_{Crd_F_i} \) is the coordination delay among the members of \( F_i \). In \( EEL \), each forwarding node waits for higher-priority nodes to respond by sending an ACK packet.

- **End-to-end transmission Cost (EC)** [143]: This metric is equal to the energy required for delivering an \( L \)-bit packet from node \( i \) to the final destination through an optimally selected cluster-parent-set (CPSi) with respect to \( R \), the communication range, which we call it \( F_{i,R} \) in our own notation:

\[
EC(i, dst) = \min_{R} (AEC(i, F_{i,R}) + REC(F_{i,R}, dst)). \quad (44)
\]

If we denote the energy cost of transmitting an \( L \)-bit packet from node \( i \) with \( E_i(L, R) \), then the first term on the right of eq. (44) represents the average energy cost of delivering an \( L \)-bit packet from node \( i \) to \( F_{i,R} \) in which:

\[
AEC(i, F_{i,R}) = \frac{E_i(L, R)}{P_{F_{i,R}}}, \quad (45)
\]

and the second term on the right shows the energy cost of delivering the \( L \)-bit packet from \( F_{i,R} \) to the final destination:

\[
REC(F_{i,R}, dst) = \sum_{jk,F_{i,R}} P(i,j)EC(j, dst) \quad (46)
\]

- **Expected Cognitive Anypath Transmissions (ECATX)** [144]: Defined in cognitive WNs, ECATX greatly resembles M-LLA and EATT structurally and also in the sense that all these three metrics revise the link probability by one factor of interest. ECATX revises the link probability by the factor of link quality:

\[
ECATX(i, F^{k}_{i}) = \frac{1}{P^{k}_{F_{i}},q^{k}_{i}} \quad (47)
\]

in which the revision factor \( q^{k}_{i} \) denotes the quality of channel \( k \) of node \( i \) in the sense of its average OFF-time duration compared to that of the other channels. A larger \( q \) indicates a greater eligibility for forwarding packets. Therefore, the end-to-end metric is defined as:

\[
ECATX(i, dst) = ECATX(i, F^{k}_{i}) + ECATX(F^{k}_{i}, dst). \quad (48)
\]

- **Expected Delivery Ratio (EDR), Expected End-to-End Delay (EED)** [11]: [11] proposes two OR algorithms for connecting Narrowband-Internet-of-Things (NB-IoT) users to a Base Station (BS) in cellular communications paradigm, via a set of duty-cycled D2D relays. The basic assumption, herein, is that the routings occur in two hops. The authors introduce two OR metrics, EDR, which tries to maximize the expected end-to-end packet delivery probability, and EED, which aims at minimizing the expected total transmission delay. The two metrics can be defined in the form of simplified optimization formulations as follows:

\[
max_{\text{relay,slot}} EDR(src, BS) = \sum_{\text{slot relay}} \sum_{\text{relay,slot}} PDP(src, relay, slot).PD\text{P}(relay, BS, slot) \quad (49)
\]
and
\[
\operatorname{min}_{\text{relay, slot}} EED(\text{src}, \text{BS}) = (\text{EDR}(\text{src}, \text{BS}))^{-1} \times \sum_{\text{slot}} \sum_{\text{relay}} \text{PDP}(\text{src, relay, slot}) \times PDP(\text{relay, BS, slot}) \times T_{TX}(\text{src, relay, slot}),
\]
wherein the \text{PDP}s and the \text{T}_{TX} are defined between \text{src}/\text{relay} and \text{relay}/\text{BS} in specific time slots. The optimization problems boil down to finding the optimum relay set and the transmission time slot.

- **Stability-Quality-Advancement (SQA) [145]**: This metric, introduced particularly for VANETs with vehicles in highways moving in the same direction, is very similar to the M-LLA metric with a modified cost:
\[
\text{SQA}(i, j) = p_{ij} \cdot s_{ij}, a_{ij}.
\]
Compared to M-LLA, the only modification is the packet relative advancement, \(a_{ij}\), defined as:
\[
a_{ij} = \begin{cases} \frac{d_{ij}}{R} & ; 0 < d_{ij} \leq R \\ 0 & ; \text{o.w.} \end{cases}
\]
The double consideration of the geographical advancement through \(s_{ij}\) (the stability index of the link connecting node \(i\) and node \(j\) as in eq. (32)) and \(a_{ij}\) in the cost function of eq. (52) may require further justification.

- **Expected Transmission Direction (ETD) [146]**: ETD is defined in the context of data transmission in IoT applications with multiple unreliable gateways. In this application, it is assumed that all sensor nodes, as well as gateways, are duty-cycled. So, not only the PDP of the individual links belonging to a specific path but the extent of duty-cycle overlaps along those links are also important. The ETD metric is defined as the cost of delivery at the minimum-cost gateway among the candidate gateways corresponding to a specific destination node, within a flexible budget of energy and delay. Assuming a number-labeled set of nodes along the path from node \(i\) to \(dst\) (i.e., the minimum cost gateway), the metric is formulated as:
\[
\text{ETD}(i, dst) = \sum_{j=1}^{d_{ij}+1} E_{\text{cond}}(j \to j+1) \sum_{m=0}^{d_{ij}} m \left(1 - p_{ij,m+1}\right) p_{ij,m+1},
\]
wherein the inner summation accounts for the transmission cost over all links \((j \to j+1)\) considering \(R_{TX}\) number of retransmission allowances, and \(E_{\text{cond}}\) denotes a link’s consumed transmission energy. It should be emphasized that [146] treats the cost to the selected gateway as the cost to the destination.

- **Segment’s Packet Delivery Ratio (SPDR), Packet Delivery Advancement (PDA) [85]**: In CRNs, the condition and the availability of links (due to spectrum variation) are changed dynamically. To overcome these limitations regarding optimal routing, [85] divides the path between \text{src} and \text{dst} into a set of smaller and more stable route segments by introducing temporary source-destination pairs. The temporary source \((\text{src}^{'})\) and destination \((\text{dst}^{'})\) are selected so that they can communicate through a single candidate set. SPDR is then defined as the classical delivery cost from \text{src}^{'\prime} to \text{dst}^{'\prime} through the candidate set using just the link probabilities as follows:
\[
\text{SPDR}(\text{src}^{'}, \text{dst}^{'}) = \sum_{i=1}^{\text{src}^{'}} p_{\text{src}^{'},i} \cdot P(i, \text{dst}^{'})\text{.}
\]
In the continuation, to make a trade-off between longer geographical advancement and shorter forwarder candidate list, [85] further amends SPDR to account for geographical progress:
\[
\text{PDA}(\text{src}^{'}, \text{dst}^{'}) = \text{SPDR}(\text{src}^{'}, \text{dst}^{'})d(\text{src}^{'}, \text{dst}^{'})\text{.}
\]

- **Expected Dynamic Transmission Cost (EDTT) [147]**: Dynamic transmission power strategy is sometimes adopted to serve energy-critical networks such as Energy-Harvesting Wireless Sensor Networks (EH-WSNs) more efficiently. However, this provides the communication links with time-varying qualities, whose information to be updated and disseminated regularly. The EDTT represents the end-to-end transmission time-cost, in the time-slotted underlying network, with the familiar two-step form (e.g., see ETC* in eq. (39)) of:
\[
\text{EDTT}(i, dst, t) = \text{EDTT}(i, j, t) + \frac{\sum_{j \in F} \text{EDTT}(j, dst, t)}{|F|}\text{,}
\]
where its single-hop counterpart is defined as:
\[
\text{EDTT}(i, j, t) = \frac{1}{p_{ij}} T_{\text{com}} T_{\text{wait}}(t)
\]
\(T_{\text{com}}\) is the average transmission time-cost and \(T_{\text{wait}}\) denotes the average waiting duration at time \(t\), throughout each time slot. We suspect that the original formulation of EDTT in eq. (7) of [147] might be erroneous, since to be opportunistic, the single-hop progress should target a forwarder list rather than a single node, which we corrected herein.

3) **Multi-Path/Per-Hop OR Metrics**: These metrics evaluate progress in a short-sighted fashion. In contrast to the two previous classes, the relevant metrics are calculated non-recursively. The metrics are presented in the chronological order of their appearance in the literature.

- **Expected One-hop Throughput (EOT) [148]**: The authors of the OEE metric [149] proposed another metric, known as EOT, which is redefined in several papers with different names and optimization goals [150–154]. In EOT, each forwarding node \(i\) selects \(F_i\), so that 1) the geographical (physical) progress of the packet toward the destination is maximized and 2) the time required for the transmission of the packet from node \(i\) to node \(j \in F_i\), \(t_{TXi}\), is minimized simultaneously. The authors decompose \(t_{TXi}\) to several components, such as the channel contention time, the data transmission time, the propagation delay, and the forwarding node coordination delay. EOT is defined as follows:
\[
\text{EOT}(i, F_i) = \sum_{j \in F_i} d_{ij} P(i, j) \frac{L}{t_{TXi} \prod_{j \in F_i} (1 - p_{ij}) + \sum_{j \notin F_i} t_{TXi} P(i, j)}\text{.}
\]
Note that $\sum_{j \in F_i} t_{TX,i,j} P(i,j)$ is the expected delay for the successful transmission of the packet from node $i$ to the members of $F_i$. Although not determined in the paper exactly, $t_{TX,i,j}$ appears to be the retransmission time of the packet, which is multiplied by $\prod_{j \in F_i} (1 - p_{ij})$, i.e., the probability that none of the members of $F_i$ receive the packet successfully. Therefore, the denominator is the excepted one-hop delay of the packet from node $i$ to $F_i$, considering both opportunistic forwarding and retransmission delays.

The first multiplicand on the RHS of eq. (58) was later named as a new OR metric, EPA [149], by the same authors.

**Expected Advancement Rate (EAR):** EAR [117] is an extension of EAR, OETT [149] proposed by the same authors. EAR models the expected bit-advancement per second by incorporating the node rate:

$$EAR(i, F_i) = r_i \sum_{j \in F_i} d_{ij} P(i,j) = r_i EPA(i, F_i) \quad (59)$$

where $r_i$ is the broadcast rate of node $i$.

**Opportunistic Expected Transmission Time (OETT):** In [117], the ETT [155] unicast metric is generalized for opportunistic routing scenarios by considering the hidden node problem. OETT is defined for the hyper opportunistic link between node $i$ and its forwarding candidate set (i.e., $F_i$) as follows:

$$OETT(i, F_i) = \frac{L}{r_i EPA(i, F_i)} \quad (60)$$

where $L$ is the packet length, and $r_i$ is the broadcast rate of node $i$. OETT measures the expected transmission time to send a packet from node $i$ to any node in $F_i$.

**Energy Distance Ratio per bit (EDRb), Delay Distance Ratio (DDR):** [156], [157] introduces two metrics related to the joint geographical progress/consumed energy and the joint geographical progress/delay. Thereafter, a routing protocol that employs Pareto optimization with a reliability constraint of these two metrics is proposed. The joint geographical progress/consumed energy metric, called EDRb, is defined as:

$$EDRb(i, F_i) = \frac{E_b}{EPA(i, F_i)} \quad (61)$$

and the joint geographical progress/delay metric, called DDR, is defined as:

$$DDR(i, F_i) = \frac{T_{hop}}{EPA(i, F_i)} \quad (62)$$

In eq. (61), $E_b$ is the energy consumption per bit, and in eq. (62), $T_{hop}$ denotes the delay of a packet being transmitted over one hop.

**Multicast Expected Advancement Rate (MEAR), I-MEAR:** MEAR [158] is a naive extension of the EAR metric to multicast applications. The MEAR of node $i$ with respect to all multicast destinations set $DST$ is defined as:

$$MEAR(i, DST) = \max_{F_i} \sum_{j \in DST} EAR(i, F_i^h) \quad (63)$$

Based on eq. (63), MEAR of a node $j$ is calculated by finding the best rate that yields the largest MEAR. The authors argue that because of the tree backbone, the destinations of node $i$ will depend on its location. Hence, they propose a modified version of MEAR named I-MEAR:

$$I-MEAR(i, DST_i) = \max_{F_i^h} \sum_{j \in DST_i} EAR(i, F_i^h) \quad (64)$$

**Expected Packet Advance (EPA), One-hop Energy Efficiency (OEE):** OEE [149] is an energy-aware metric proposed for WSNs using the physical location of sensor nodes. Node $i$ selects members of $F_i$ so that, simultaneously, 1) the geographical progress of the packet toward the destination is maximized and 2) the energy consumed for the successful transmission of the packet (denoted by $E_{or}(F_i)$) is minimized. $E_{or}(F_i) = E_i + E_F + E_o$ is composed of three parts: 1) $E_i$, the expected energy consumed by node $i$ for transmitting the packet, 2) $E_F$, the expected energy consumed by the members of $F_i$ when dealing with the packet, and 3) $E_o$, the expected energy consumed by other neighbors of node $i$. Each of these parts is further decomposed into the power consumption required for data reception, data transmission, and idle listening. Then, the expected packet advancement (EPA) of a packet is defined as:

$$EPA(i, F_i) = \sum_{j \in F_i} d_{ij} P(i,j) \quad (65)$$

where $d_{ij}$ is the geographical advancement of the packet from node $i$ to node $j$:

$$d_{ij} = d(i, dst) - d(j, dst) \quad (66)$$

Finally, the OEE metric is defined as follows:

$$OEE(i, F_i) = \max_{p \subseteq C_i} \left\{ \frac{EPA(i, F_i)}{P_{F_i}, E_{or}(F_i)} \right\} \cdot L \quad (67)$$

In eq. (67), $EPA(i, F_i)$ is the expected packet advancement for a successful opportunistic forwarding considering retransmissions, and $F_i^h$ is a subset of $C_i$ which maximizes OEE.

**Expected Distance Progress (EDP):** EDP is a recursive opportunistic metric based on the Distance Progress OR (DPOR) [77], an earlier work from the same authors, which considers the distance progress of the data packet toward $dst$. The EDP’s definition is similar to the EPA’s definition given in OEE [149].

**Cognitive Transport Throughput (CTT):** [160] introduces an OR metric in multi-hop CR networks, although the metric itself is calculated over a one-hop relay:

$$CTT(i, F_i^k) = \sum_{j \in F_i^k} p^k(i,j) \cdot \frac{L d_{ij}}{T_{RX}(j)} \quad (68)$$

wherein $k$ and $T_{RX}(j)$ are respectively the channel index and the reception delay of node $j$. The metric measures
the expected bit advancement per second for the one-hop relay of an $L$-bit packet in channel $k$. \[160\] states that maximizing the one-hop relay performance contributes to the end-to-end performance improvement.

- **Forwarder Score (FS) \[161\]**: This metric is a direct derivative of EDC that provides load balancing through the consideration of the forwarding node’s residual energy in duty-cycled WSNs. FS is defined as:

$$FS(i, F_i) = \frac{1}{E_{res,i}(|F_i| + 1)} + \frac{\sum_{j \in F_i} FS_j}{|F_i|} \quad , (69)$$

where $E_{res,i}$ denotes the scaled residual energy ratio of node $i$, and $\alpha$ is a weight for adjusting the effect of the residual energy.

According to \[161\], the probability that a node overhears another neighboring node’s transmission increasingly depends on the overheaded node’s number of neighbors. However, this statement is not entirely justified.

- **Expected single-hop packet speed (espeed) \[162\]**: QoS-aware geographic opportunistic routing in WSNs, introduced in \[162\], considers both end-to-end reliability and delay constraints and formulates the routing as a multi-objective multi-constraint optimization problem. Regarding the forwarder list formation, let $\pi_j(F_i) = \{j_1, j_2, ..., j_n\}$ be one ordered permutation of nodes in $F_i \in C_i$ with priority ($j_1 > j_2 > ... > j_n$), then the espeed metric is defined as the solution to the following maximization problem:

$$espeed(i, F_i) = \max_{\pi_j(F_i)} \frac{EPA(i, \pi_j(F_i))}{ed(i, \pi_j(F_i))} \quad , (70)$$

wherein EPA and ed represent the expected packet advancement per-hop mentioned previously and the expected single-hop media delay, respectively, and both are limited to corresponding predetermined thresholds. Also, it is assumed that all members of the forwarder list can hear each other.

- **Patterned Synchronization Tendency Metric (PSTM) \[163\]**: To prevent the overuse of nodes due to the patterned synchronization effect \[163\] in duty-cycled WSNs, the value of PSTM at each forwarding node is compared against a threshold. The results of the comparisons are then used to adjust the duty-cycle of the node. PSTM is defined as:

$$PSTM(i, S_i) = \frac{\sum_{j \in S_i} P(i \leftrightarrow j)}{|S_i|} \quad . (71)$$

$P(i \leftrightarrow j)$ denotes the probability of node $j$ to select the particular upstream node $i$ as the next-hop forwarder, and $S_i$ is the set of nodes to which node $i$ acts as the upstream node. Node $i$ is informed of $P(i \leftrightarrow j)$, which is calculated at node $j$, through the header field of the transmitted packets from node $j$ to node $i$.

- **Distance Utility Energy Ratio (DUER) \[164\]**: The DUER metric, which is similar to its predecessors EDRb and DDR \[156\], is a normalized version of EPA aiming to maximize the network’s lifetime. DUER is defined as:

$$DUER(i, F_i) = \frac{EPA(i, F_i)}{E_{tot}(i, F_i)} \quad . (72)$$

Herein, $EE_{tot}$ is a utility function that adds up the energy consumed by node $i$ and members of $F_i$ for packet transmission and reception.

- **Forwarding Efficiency (FE) \[165\]**: FE is a multi-flow metric. Here, we present FE for a single flow:

$$FE(i, F_i, r) = \frac{EPA^*(i, F_i, r) \cdot r}{E_{F_i}} \quad , (73)$$

where $r$ is the transmission rate, and $EPA^*$ is defined as follows:

$$EPA^*(i, F_i, r) = \sum_{i \in F_i} d_{ij}r_{ij} \sum_{j=0}^{\infty} (1 - p_{ik} \Delta_k) \quad . (74)$$

In eq. \[74\], $\Delta_j$ is the probability that the coded packet is decodable at the $j$-th forwarding node.

- **Expected Energy and Packet Advancement (EEPA) \[166\]**: In UWSNs, which feature a 3D topology, high possibility of void regions, and the underwater acoustic propagation model, this metric aims at compromising between the normalized reliability (associated with the first term on the RHS of the equation below) and the normalized energy consumption (associated with the second term) and is defined as:

$$EEPA(i, F_i) = \alpha \frac{EPA(i, F_i)}{E(i, C_i)} - \beta \frac{E(i, F_i)}{E(i, C_i)} \quad . (75)$$

wherein $F_i$ is a subset of $C_i$ which maximizes the above expression. EPA, the expected packet advancement, is a variant of the EPA metric in eq. \[65\] which assigns a higher priority to a forwarding node with lower underwater depth. $E$ denotes the consumed energy of the forwarder list in the packet forwarding process. $\alpha$ and $\beta$ are the weighting coefficients to favor one factor to another. Since both fractions in eq. \[75\] are normalized and between zero and one, though not mentioned in the original paper, we suspect that most probably the minus operator should be an addition and $\alpha + \beta = 1$ ($0 \leq \alpha, \beta \leq 1$).

- **Forwarder Score (FS) \[167\]**: This metric, as its identically-titled predecessor \[161\], aims at providing water depth.

\[6\] The $*$ superscript is intended for distinction with the EPA metric in eq. \[74\].
\[7\] The $*$ superscript is intended for distinction with the FS metric in eq. \[69\].
- Enhanced Expected Packet Advance (EEPA\(^*\)\[^{[168]}\]): There is another version of EPA, called EEPA\(^*\), that also considers, in a more realistic scenario, the correlation between contributing links in packet delivery from a node to a specific forwarder list. Specifically, EEPA\(^*\) revises the term \(P(i, j)\) (see eq. (2)) in eq. (65) as:

\[
P_c(i, j) = p_{ij} \prod_{m=1}^{i} (1 - p_{im} \rho(i, j, m)) ,
\]

where \(\rho(i, j, m)\) denotes the correlation between the \(i \rightarrow j\) and \(i \rightarrow m\) links. Therefore, the final derivation for EEPA\(^*\) becomes:

\[
EEPA^*(i, F_i) = \sum_{j \in F_i} d_{ij} P_c(i, j) .
\]

- Radio Signal Strength Indicator (RSSI)-based Metric (M-RSSI\[^{[84]}\]): This over-link metric is introduced in \[^{[84]}\] for a duty-cycled network-coded WSN to represent the link quality. The metric, which is based on the RSSI between two nodes, is a compromise between the path length and the PDP of the link connecting them. The M-RSSI metric is calculated by:

\[
M-RSSI(i, j) = \begin{cases} 1 + \gamma \quad &\text{if } \text{RSSI}_{ij} < \text{RSSI}_{ij}^{\text{THRSLD}} \\ 0 \quad &\text{otherwise} \end{cases}
\]

wherein the parameters \(\text{RSSI}_{ij}^{\text{THRSLD}}\) and \(\gamma\) are tuned experimentally. The degradation of RSSI below \(\text{RSSI}_{ij}^{\text{THRSLD}}\) Penalizes by \(\gamma\) in the metric's value to avoid long links.

- Dempster-Shafer Theory (DST)-based Trust (DSTT\[^{[83]}\]): This metric, presented in the context of a UAWSN application, combines three pieces of environmental evidence. Each evidence represents a single-objective metric based on DST. The target objects are the residual energy, the PDP, and the geographical advancements of the next hop. Using the Basic Probability Assignment (BPA) function, a mass value is assigned to every node \(j \in C_i\), denoting its strength as a piece of evidence. The mass values corresponding to the above three metrics are then defined as:

\[
\begin{aligned}
m_1(i, j) &= \sum_{h \in C_i} E_{\text{res}}(j) E_{\text{res}}(h) \\
m_2(i, j) &= \frac{p_{ij}}{\prod_{h \in C_i} p_{ih}} \\
m_3(i, j) &= \frac{d(i, j)}{\sum_{h \in C_i} d(i, h)}
\end{aligned}
\]

\[^{[83]}\] uses the Dempster's rule of combination from multiple metrics to get the trust value of node \(j\) as a forwarding node for node \(i\) as follows:

\[
DSTT(i, j) = \frac{m_1(i, j) \cdot m_2(i, j) \cdot m_3(i, j)}{1 - K} ,
\]

where \(K\) is a normalization factor used to measure the conflict between BPA functions of different metrics. The nodes from \(C_i\) are added to \(F_i\) (node \(i\)'s forwarder list) and prioritized in decreasing-trust order. The addition of nodes to \(F_i\) continues until \(P_{F_i}\), (see Table \[^{[11]}\]) reaches a predetermined minimum threshold.

- Effective Forwarding Rate (EFR\[^{[81]}\]): \[^{[81]}\] introduces EFR in the context of Cognitive Radio Ad-hoc Networks (CRAHN) wherein the authors address the volatility in link states by their effective forwarding rates. The EFR metric is defined as:

\[
EFR(i, F_i, r_i) = r_i \sum_{j=1}^{\#F_i} p_{ij} P(i, j) ,
\]

in which \(r_i\) denotes the transmission rate emanated by node \(i\). Though EFR might seem like a new metric, aside from the multiplicative factor \(r_i\), which is independent of the forwarding links' states, it is completely similar to the classical PDP-based metrics.

- Distance Progress (DP), Expected Distance Progress (EDP\[^{[79]}\]): Assuming an Underwater Optical Wireless Network (UOWN) environment where each node is aware of its location information as well as its one-hop neighbors', \[^{[79]}\] introduces the following geographical-advancement metric:

\[
DP(i, j) = ||d_{\text{src}} - d_{\text{dst}}|| - ||d_j - d_{\text{dst}}|| , \forall j \in F_i ,
\]

for \(\text{EDP}^*(i, F_i)\): is modified by averaging over all members of the node \(i\)'s forwarder list, \(F_i\):

\[
EDP^*(i, F_i) = \sum_{j \in F_i} DP(i, j) P(i, j) .
\]

DP and EDP\(^*\) are very similar to, with minor differences, the geographical advancement definition in eq. (66) and the EPA metric in eq. (65), respectively.

4) Single-Path/Per-Hop OR Metrics:
- Metric of the Most Probable Path protocol (M-MPP\[^{[76]}\]): This metric measures the degree to which a link capacity can satisfy a connection request in bits/second. For a given CR connection request of rate demand \(D\) (in bits/second), the probability that channel \(k\) can support this demand, using Shannon theorem, is given by:

\[
P[C_{ijk}^{k} \geq D] = P\left[ S_{l, i}^{(k)} \leq \frac{S_{RX, j}^{(k)}}{2 \pi^2} - G_0 \right] ,
\]

where \(k\) is the * superscript is intended for distinction with the EDP metric.

The abbreviation is from the authors of this survey for better reference.
where $B^k$ is the channel $k$’s bandwidth, $S_{RX,ij}^{(k)}$ and $S_{TX,ij}^{(k)}$ represent the received signal power from node $i$ at node $j$ and the total primary-to-CR interference power at CR node $j$, respectively, and $G_0$ denotes the white Gaussian noise power spectral density.

- **Trustworthiness and ETX (E2TX)** [52]: The ETX metric estimates the PDP of a wireless link using periodic measurements and then trusts these measurements for the next 5 or 10 minutes. In E2TX, the trustworthiness of the ETX metric is revisited. The trust index of node $j$ assigned by node $i$ after the $n$-th topology update cycle is defined as follows:

$$Trust(i, j, n) = \frac{\theta_{ij}(n)}{N_{ij}(n)}, \quad (86)$$

where $N_{ij}(n)$ is the number of packets forwarded by node $i$ toward node $j$ in time slot $n$. $\theta_{ij}(n)$ is the number of packets correctly received by node $j$ in the same time slot. After each new observation in the $(n+1)$-th topology update cycle, $Trust(i, j, n)$ is calculated by using a moving average window model similarly to the RTT computation in TCP (RFC2988 [170]):

$$Trust(i, j, n+1) \leftarrow \alpha.Trust(i, j, n) + (1 - \alpha).Trust(i, j, n+1), \quad (87)$$

where $\alpha$ is a positive weighting factor smaller than 1.

Finally, the E2TX metric is defined as follows:

$$E2TX(i, j, n) = (1 - Trust(i, j, n)).ETX(i, j, n), \quad (88)$$

In this equation, the E2TX for a trusted link is less than the original link’s ETX. Trust opportunistic multicast Routing (TOMR) [171] has used the E2TX metric to design a secure multicast protocol.

- **Probability of Success (PoS)** [172], [173]: PoS defines the probability of the channel availability period being greater than or equal to the required transmission period between two neighboring nodes in a specific channel. For two neighboring nodes $i$ and $j$ communicating in channel $k$, the metric is equal to:

$$PoS^k(i, j) = P[T_{avl}^k(i, j) \geq T_{TX}^k(i, j)], \quad (89)$$

wherein $T_{TX}^k$ denotes the transmission time and the channel availability time period, $T_{avl}^k$, is assumed to follow an ON/OFF state model.

- **Dynamic Forwarding Delay metrics (DFD)** [174], [175], [176], [177], and [178]: These are a family of very similar OR metrics introduced in different wireless network types by almost common authors. The original forms of the metrics suffer from the poor choice of notation, and we, herein, reformulate them into as consistent as possible forms. The objective of these metrics is to minimize the forwarding delay by considering a linear combination of multiple factors, the link quality, the geographical advancement, the residual energy, and the queue population of the forwarding relays.

In the context of WANETs [174] and IoT [175], DFD$_1$ is defined as:

$$DFD_1(i, j) = (\alpha_1 \cdot f_1(D_{res})) + \alpha_2 \cdot f_2(LQI_{ij}) + \alpha_3 \cdot f_3(d(j, dst)) \cdot DFD_{max}, \quad (90)$$

in the context of MANETs [176], DFD$_2$ is defined as:

$$DFD_2(i, j) = (\alpha_1 \cdot f_1(D_{res})) + \alpha_2 \cdot f_2(LQI_{ij}) + \alpha_3 \cdot f_3(d(j, dst)) + \alpha_4 \cdot Live(i, j) \cdot DFD_{max}, \quad (91)$$

and in the context of WSNs [177], DFD$_4$ is defined as:

$$DFD_4(i, j) = (\alpha_1 \cdot f_1(D_{res})) + \alpha_2 \cdot f_2(d(j, dst)) + \alpha_3 \cdot EOF(j) \cdot DFD_{max}. \quad (92)$$

In the above equations, $DFD_{max}$ is the predefined maximum delay allowed on each link, the sum of $\alpha$s totals 1, and the contributing functions are defined as follows:

$$f_1(D_{res}) = \begin{cases} \frac{E_{init} - E_{res}}{E_{init}} & ; E_{res} \geq E_{min} \\ 0 & ; E_{res} < E_{min} \end{cases}, \quad (93)$$

$$f_2(LQI_{ij}) = \begin{cases} 1 & ; LQI(i, j) \geq LQI_{j}^{bad} \\ \frac{LQI_{j}^{max} - LQI(i, j)}{LQI_{j}^{max}} & ; LQI_{j}^{bad} \leq LQI(i, j) < LQI_{j}^{good} \\ 0 & ; LQI(i, j) < LQI_{j}^{good} \end{cases}, \quad (94)$$

$$f_3(d(j, dst)) = \begin{cases} \frac{2R - d(j, dst)}{2R} & ; d(j, dst) \geq R \\ 0 & ; d(j, dst) < R \end{cases}, \quad (95)$$

$$LIVE(i, j) = \frac{1}{\frac{180 - \theta(i, j)}{180}} \cdot \frac{1}{T_{LV}(i, j)}, \quad (96)$$

and

$$EOF(j) = \frac{EDR(j)}{E_{res}}, \quad (97)$$

wherein $f_1$ and Energy Objective Function (EOF) reflect the effect of the residual energy, $f_2$ represents the link quality, and $f_3$ and $LIVE$ represent the impacts of the geographic advancement and mobility. The parameters Link Quality Indicator ($LQI(i, j)$) [178], $\theta(j)$, $T_{LV}(i, j)$, and Energy Drain Rate ($EDR(j)$) denote the link $ij$’s quality measure, the angle between the node $j$’s moving direction and the virtual line connecting the source and the destination, the stability period of link $ij$, and the rate at which node $j$ loses its energy, respectively.

In a similar way, except in the context of video dissemination over FANETs [1] and with differently defined constituent functions, DFD$_3$ is defined as:

$$DFD_3(i, j) = (\alpha_1 \cdot f_4(LQI_{ij}))+ \alpha_2 \cdot f_5(d(j, dst)) + \alpha_3 \cdot f_6(Q(j)) \cdot DFD_{max}, \quad (98)$$

The index is intended for distinction between different DFD metrics.
in which the constituent functions \( f_4, f_5, \) and \( f_6 \) represent the link quality, the geographic advancement, and the relaying node’s congestion status, respectively. The functions \( f_4 - f_6 \) are:

\[
f_4(LQI(i,j)) = \frac{1}{1 + e^{-c_3(LQI(i,j) - c_2)}} \quad , \quad (99)
\]

\[
f_5(d(j,dst)) = \frac{1}{1 + e^{-c_3(d(j,dst) - R)}} \quad , \quad (100)
\]

\[
f_6(Q(j)) = \frac{1}{1 + e^{-c_4(Q(j) - Q_{max})}} \quad , \quad (101)
\]

in which \( j' \) is the intersection between the node \( j \)'s communication range boundary and the \( src - dst \) virtual connecting line, \( Q(j) \) is the node \( j \)'s queue population, the sum of \( os \) totals 1, and \( cs \) are the adopted models’ constants.

- **M-SGOR** [179]: This metric prioritizes neighboring nodes (i.e., \( i \rightarrow j \in C_i \)) based on their geographical advancements toward the destination and total trust levels (a linear combination of direct and indirect trust), in insecure WSNs. The metric considers a linear combination of advancement and trust as follows:

\[
M-SGOR(i,j) = \beta(1 - \frac{d(j,dst)}{d(i,dst)}) + (1 - \beta)\text{Trust}_{ij},
\]

wherein varying \( \beta \) from 0 towards 1 gradually favors the advancement over the trust.

- **Reliable Trust-based OR (RTOR), TORDP, GEOTOR**: [180] and [181] consider the trustworthiness of a neighboring node as well as its link reliability by defining a new metric, RTOR. Each node \( i \) calculates its neighboring node \( j \)'s RTOR according to the following:

\[
RTOR(i,j) = \text{Trust}_{ij} \cdot p_{ij}, \quad (103)
\]

where \( \text{Trust}_{ij} \) denotes the trust value (\( \in [0,1] \)) of node \( j \) from node \( i \)'s perspective. The trust value is updated periodically based on the number of uncooperative interactions between node \( i \) and node \( j \). This local metric is then used for selecting the candidate forwarder set [180].

Assuming that the geographical locations of all the nodes are available, TORDP limits the candidates set’s size to include only members that can contribute more than a predetermined minimum geographical advancement (distance progress), MinDP, towards the final destination. Therefore, TORDP is defined as:

\[
TORDP(i,j) = \begin{cases} 
\text{Trust}_{ij} \cdot p_{ij} & \text{if } DP(i,j,dst) \geq \text{MinDP} \\
0 & \text{otherwise}
\end{cases} \quad (104)
\]

where \( DP(i,j,dst) \) represents the additional geographical advancement towards the final destination obtained by going from node \( i \) to node \( j \).

Finally, GEOTOR incorporates the distance progress, \( DP(i,j,dst) \), into an OR metric, as below:

\[
GEOTOR(i,j) = \text{Trust}_{ij} \cdot p_{ij} \cdot DP(i,j,dst).
\]

\[
\quad (105)
\]

14\text{The abbreviation is from the authors of this survey for better reference.}

- **Energy and Trust Aware Opportunistic routing (ETOR)** [33]: This metric is defined in terms of OR in slotted Cognitive Radio Social Internet of Things (CR-SIoT). ETOR comprises three factors, namely social tie, energy consumption, and trust. The metric measures the social tie and trust between a node \( i \) and a member of its next-hop candidate forwarder set \( j \) during slot time \( T \). Moreover, ETOR accounts for the residual energy of that member, as follows:

\[
ETOR(i,j,T) = \alpha_1\text{Trust}_{ij}(T) + \alpha_2E_{res}(T) + \alpha_3ST_i(T) \quad .
\]

In eq. (106), \( \text{Trust}_{ij} \) and \( ST_i \) represent the total trust (direct and indirect) and the social tie between nodes \( i \) and \( j \), respectively. \( E_{res} \) accounts for the residual energy of node \( j \). The parameters \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) provide a weighted average over these three factors.

- **Opportunistic Routing based Distance Progress (ORDP), Expected Packet Progress (EPP)** [182]: These metrics are proposed for UWSNs:

\[
ORDP(i,dst) = d(src,dst) - d(i,dst) \quad (107)
\]

and

\[
EPP(i,j) = ORD(i,dst) \cdot E_{res} \cdot p_{ij}. \quad (108)
\]

The geographical progress of a node is inherently an end-to-end metric; however, there is nothing new about ORDP except that, as opposed to the traditional definition of geographical progress, it becomes bigger by the node getting closer to the destination. The second metric combines the geographical progress, the residual energy, and the PDP of the next hop link.

- **Four Distributions (4-D)** [91], [183]: By adopting 4-D metric, the OR protocol in [91], and later in [183], try to assign higher priorities to the relay nodes which are geographically further away from the source, closer to the destination, vertically closer to the virtual line connecting the source to the destination, and finally have higher residual energy available. The 4-D metric achieves the latter by multiplying the appropriate probability distribution function corresponding to each factor:

\[
4-D(i,j) = d(i,j) \cdot \theta(i,j) \cdot dp(i,j) \cdot E(i,j) \quad \forall j \in C_i \quad ,
\]

in which \( d(i,j) \), \( \theta(i,j) \), \( dp(i,j) \), and \( E(i,j) \) are the transmission-distance distribution, the direction distribution, the perpendicular-distance distribution, and the residual energy distribution, respectively. Despite of the claim that the 4-D metric is an end-to-end metric, it looks like to be otherwise.

- **Routing Metric (RM)** [80]: In the context of WSNs for IoT, this metric, which apparently does not offer any specific novelty, linearly combines the one-hop geographical progress times the one-hop link trust, and the residual energy of the next-hop node as follows:

\[
RM(i,j) = \alpha d(i,j) \cdot \text{Trust}_{ij} + (1 - \alpha)E_{res} \quad \forall j \in F_i, \quad 0 < \alpha < 1
\]

15\text{The abbreviation is from the authors of this survey for better reference.}
Traffic-Differentiated Secure Opportunistic Routing (DSOR) \[184\]: In the context of MANETs, TDSM quantifies a node’s forwarding capability (price), which is then used by an auction-based forwarder list selection to guarantee the QoS of different types of traffic flows in an adversarial network scenario. The metric considers the node’s trust level (i.e., direct and indirect), available resources (i.e., energy and bandwidth), and service potential (i.e., ETX) for each type of flow. It is defined as the summation of two prices (or equivalently, costs), resources ($c_{rsc}$) and service ($c_{srv}$) as follows:

$$TDSM(i,j,k) = c_{rsc}(j) + c_{srv}(i,j,k) ,$$

with:

$$c_{rsc}(j,k) = \frac{1}{2} \left( \frac{E_{totj} - E_{resj}}{E_{totj}} + \frac{E_{consj}}{E_{resj}} \right) + \frac{k_{max}}{k_{max} - k + 1} \left( \log_2 \left( \frac{B_{newj}}{B_{totj} - B_{curj}} \right) \right)$$

$$c_{srv}(i,j,k) = \left( 1 - Trust(i,j) \right) + \frac{ETX(i,j,T)}{ETX(i,dst)} ,$$

wherein $ETX$, $E_{res}$, and $E_{cons}$ are node j’s initial energy, residual energy, and required forwarding energy, respectively. $B_{newj}$, $B_{totj}$, and $B_{curj}$ denote node j’s new task bandwidth requirement, total bandwidth available, and current bandwidth consumed, respectively. Finally, $k_{max}$ and $k$ represent the highest priority in the traffic flows and the priority of the k-type traffic flow.

We conclude this section with the following remarks:

- There are several OR protocols in the literature which do not explicitly mention their embedded OR metrics, for instance: MOR [186], Max-SNR [187] [89], BAOR [188], EnOR [189], OSTD [190], ELECTION [191], EECOR [192], I-AREOR [92], GEDAR [94], ODYSSE [193], ENS-OR [194], EasyGo [195], CBRT [196], GOCR [197], ECS-OR [198], Parallel-OR [199], CITP [93], SOCGO [200], EOR [201], Dice [202], AREOR [95], RPORSO [98], POR [203], PCR [204], CAOR [205], and PCon [97].

- There are several OR protocols in the literature which do not explicitly mention their embedded OR metrics, for instance: MOR [186], Max-SNR [187] [89], BAOR [188], EnOR [189], OSTD [190], ELECTION [191], EECOR [192], I-AREOR [92], GEDAR [94], ODYSSE [193], ENS-OR [194], EasyGo [195], CBRT [196], GOCR [197], ECS-OR [198], Parallel-OR [199], CITP [93], SOCGO [200], EOR [201], Dice [202], AREOR [95], RPORSO [98], POR [203], PCR [204], CAOR [205], and PCon [97].

- Mobility Awareness: Mobility (movement pattern, speed, etc.) affects the performance of the routing protocol in a network. If the OR metric employed by the
routing protocol considers mobility effects, it is called a mobility-aware metric [31]. Mobility awareness narrows the target networks into mainly MANETs and VANETs.

- **Energy Awareness:** OR metrics that include energy considerations of the relaying nodes, such as the remaining energy (residual energy), the energy consumption rate, and the capability of energy renewal, are called energy-aware [108], [109], [122], [123], [136]. Due to this core energy consideration, the scope of the target networks includes mainly WSNs.

- **Delay Awareness:** While the delay is an important factor in almost all the WNs, delay-sensitive applications require strict attendance to the temporal behavior of the network. The OR optimization methods applied to networks carrying this type of traffic should employ metrics that directly consider the time information of the traffic. Some potential target networks that employ delay-aware metrics are the CR networks [107], WMNs [133], [148], [156], and WSNs [142].

- **Channel Multiplicity:** In WNs, where the PHY and MAC layers support different frequency channels (i.e., channel selection), OR can benefit from increased degrees of freedom. Graphs can model Multi-channel networks with multi-link edges. In these networks, an appropriate channel selection is added to the problem of traditional OR routing. Some OR metrics reflect this capability [132], [133], [144]. Due to the complexity of the transceivers involved, the target nodes include WMNs and CRNs.

**TABLE IV: OR Metrics: Quick Reference**

| Features         | Target Platform | Related Protocol | Other Notable Features |
|------------------|-----------------|------------------|------------------------|
| Mobility Awareness | WN              | OAPF             |                        |
| Energy Awareness  | WN              | MORE             |                        |
| Delay Awareness   | WN              | LtMOR, MGOR      |                        |
| Channel Multiplicity | WN      | SMAF, MAP       |                        |
| Flow Multiplicity | MANET           | QoSRENI          |                        |
| Rate Multiplicity | WN              | FORLC            |                        |
| Scope             | WSN             | EFFORT           |                        |
| Method            | WSN             | N/A              |                        |

**End-to-End**

- **Multi-path**
  - EAX [111], [112]
  - EOTA [138]
  - EXACT [139]
  - EMT [141]
  - EATT [121], [138]
  - OptEOM [148]
  - STR [113]
  - OEC [124], [125]
  - EDC [128], [129]
  - ETC [131], [136]
  - EAP [137], [138]
  - EOC [137], [138]
  - -EAX [121], [138]
  - MEATT [132]
  - KAD [124]
  - -EWAES [132], [135]
  - -M-LLA [125]
  - ORCS [139]
  - ETC [137]
  - ECG [139]
  - EEP [139]
  - EEL [140]
  - EC [131]
  - -ECATX [144]
  - ECAT [121], [135]
  - -VANET [145]
  - -MMSR [106]
  - -OLT [107]
  - -ESC [108]
  - -M-ORAC [109]
  - -Q-ETX [38]
  - -M-SNR [110]

**Single-path**

- ETX [131], [136]
- mETX [105]
- ENT [105]
- M-Markov [106]
- ORL [107]
- EOC [139]
- M-ORAC [109]
- Q-ETX [38]
- M-SNR [110]
### TABLE IV: OR Metrics: Quick Reference (continued).

| Features | Target Platform | Related Protocol | Other Notable Features |
|----------|-----------------|------------------|------------------------|
| Delay Multiplicity | | | |
| Flow Multiplicity | | | |
| Rate Multiplicity | | | |

#### Rate Multiplicity:
Similar to channel multiplicity, provided that PHY and MAC layers support different transmission rates, OR can increase performance by adapting the transmission rate to the network status. Wireless networks employing this feature include WMNs [117–119], [132], [158].

#### Flow Multiplicity:
The OR mechanisms that work well when a single flow is present in the network might not do so in scenarios where multiple flows are present. In fact, increasing the number of flows results in some mutual impacts that are not traditionally reflected in single-flow metrics. Moreover, increasing the number of flows beyond one leads to inter-flow priority and queuing issues in common forwarding nodes. While the multi-flow consideration can be a concern of the OR mechanism itself, in some cases, this consideration is embedded inside the metric. Multi-flow metrics exist in two forms: metrics with different values for each flow [133] and metrics with a single value that considers the combined effects of all flows crossing a single common node. In the latter case, inter-flow NC is usually also present [165]. WMNs are potential candidates for employing multiple flow metrics in their OR mechanisms.

For each metric, Table IV summarizes all the classification information from section III-C, the features information reported earlier in this section, the target platform, and the employing OR protocol (if applicable) in a visual-friendly manner for quick referencing. One can easily select an OR metric from Table IV for the routing application in hand, by merely looking earlier in this section, the target platform, and the employing OR protocol (if applicable) in a visual-friendly manner for quick referencing. One can easily select an OR metric from Table IV for the routing application in hand, by merely looking
TABLE V: List of OR metrics employed by several OR protocols.

| Routing Metric | Protocol |
|----------------|----------|
| ETX            | EXOR [39], Economy [59], SOAR [41], MORE [27], CodeOR [66], XCOR [67], O3 [206], SlideOR [207], CCAK [65], OMNC [208], Consort [58], MaxOPP [209], ORPL [210], CAOR [271], TORP [272], ORPSN [213], CAR [217], CORMAN [60] |
|                | ExOR compact [215], NCOR [216], WBFL [217], E-MORE [218], VIMOR [219] |
| EAX            | LCAR [47], OAPF [111], ORDF [220], ABF, SAF [119], EAX LCAR [47], OAPF [111], ORDF [220], ABF, SAF [119] |
|                | MABF, SMAF [119], CoRoute [221], CRAHN [222], PLASMA [113], ROMP [114], DSM [223], CO Route [221], CRAHN [222], PLASMA [113], ROMP [114], DSM [223], COMO [224] |
|                | EDC ORW [124], ORPL [225], ORPL-DT [32], DOF [226], Staffetta [227], COF [96] |
|                | M-MPP MPP [169], MaxPoS [172] |
| PoS            | MaxASA, MinTT [172], MPOS [228] |
| FS*            | ORR [167], MORR [229] |
| EPA            | EGOR [149], GEDAR [230], [231], HydroCast [232], GOC [233], EQGOR [162], U-OR [164] |

Fig. 12: Chronological introduction of OR metrics.

E. OR Metrics: Comparative Simulations

We would like to, herein, investigate the very much critical dependency of the network performance on the choice of the OR metric, OR protocol, and the network topology. In some cases, the dependence might not be so obvious. Regarding the latter, it is interesting to see that an OR protocol applied to a particular network topology might favor a specific OR metric in terms of performance.

In the following, we consider only OR metric representatives of the single-path/end-to-end, multi-path/end-to-end, and the multi-path/per-hop classes and compare their performances, through simulation, under the same OR protocol for different topology scenarios. The exclusion of the single-path/per-hop class of OR metrics is because of its obvious underperformance due to both not benefiting from the broadcast nature of the wireless medium and limited vision (i.e., not foreseeing communication holes/dead-ends and unreliable links ahead). The scenarios are intentionally selected to highlight different-in-nature topologies.

ETX, EAX, and EPA are selected as the representatives of the three OR metric classes. Although not originally introduced as an OR metric, ETX [104], the metric used by the first and many subsequent OR protocols, is selected as the representative of the single-hop/end-to-end class. We select EAX, the first OR-dedicated metric introduced, as the representative of the multi-hop/end-to-end OR metric class. EAX defines the opportunistic anypath cost as the expected number of transmissions the source must make for the successful delivery of a packet to the destination. Most of the metrics in this class are derived from EAX (e.g., by considering extra parameters, as in M-LLA, which considers mobility). EPA represents the multi-path/per-hop class of OR metrics. EPA, which defines the geographical advancement of a packet in each hop towards the destination, has inspired many other OR metrics in this class. Regarding the fair comparison noted previously, the above-selected metrics use only the PDP parameter in their definitions.

To investigate the impact of different choices of OR metrics on network performance, we choose EXOR [39] as the base OR protocol. EXOR, introduced as the first OR protocol, benefits from the broadcast nature of the wireless transmission and considers multiple forwarders in a network with low-quality links. EXOR incorporates the functionality of the MAC layer into the routing protocol by scheduling the transmission
Fig. 13: Investigation of how the representative OR metrics, ETX, EAX, and EPA, perform in a variety of topology scenarios with different progress patterns. Left: Topology scenarios. Right: Performance results.
times of multiple forwarders. The scheduling is achieved by prioritizing forwarders based on their ETX metrics. In EXOR, the concept of the packet is replaced by a batch, and the batch-map transmission obviates the use of ACKs.

In terms of the topology, we test five different representative topology scenarios with distinguishing natures (left column of Fig. 13). The topology scenarios have been designed to represent different progress patterns while avoiding communication holes.

The EXOR protocol was implemented in the OMNET++ simulator using the MiXiM wireless framework. OMNET++ was chosen because of its good performance, modularity, and the ability to separate node behavior from node parameters, where the latter feature facilitates running large parameter studies. In line with our investigation purpose, the prioritizing metric in the original EXOR (i.e., ETX) is replaced by EAX and EPA, one at a time. We model the channel fading effect as proposed in \[236\], with \( R = 200 \) m representing the wireless half-reach radius. The network is a 600 m*300 m rectangle. \( src \) and \( dst \) are located at the two ends of the rectangle, 600 m apart. Therefore, \( src \) cannot directly communicate with \( dst \), but it requires at least one forwarding node for communication. The simulation for each topology-metric pair is repeated 50 times to obtain 95% confidence intervals. The repetitions differ concerning the random locations of the nodes inside their confining blocks. In each run (repetition), \( src \) sends one batch of data packets (which includes one hundred 1500B-long data packets).

Some important facts observed based on the simulation results are as follows:

- For some topologies (Figs. 13a,b,c), the delay results are almost indifferent to the choice of metric. As an extreme case, the progress-based (EPA) and path-quality-based (ETX and EAX) prioritization (scheduling) result in the same performance in the pure longitudinal topology scenario of Fig. 14.

- The employed metrics perform differently in each topology. The illustrated topologies are arranged in order of decreasing performance. The best results are observed for the case where the forwarding nodes are arranged in increasing progress preference though being allowed to adopt random locations laterally within their confining blocks (i.e., the forwarding nodes are spread longitudinally across the network, Fig. 13a). This result is expected in this case because the forwarding nodes have a wide range of link qualities to the source, which allows them to contribute to the forwarding task incrementally. In fact, in this case, the scheduling concept is in the best possible way.

- The underperformance of the topology scenario of Fig. 13b compared to Fig. 13a is partly due to the existence of one low-quality long hop and partly due to the redundant forwarding contribution role of each of the two forwarding groups.

The redundancy problem above is intensified in the topology scenario of Fig. 13c. The topology scenario of Fig. 13d shows slightly worse performance than that of Fig. 13e because of the existence of more low-quality hops. Finally, the worst performance is demonstrated in the topology scenario of Fig. 13e. In this scenario, in addition to the existence of low-quality long hops, the cumulation of redundant forwarding nodes around the source (which happens to be the first-hop relay node) gives the source an overly optimistic view of packets forwarded through the transmission of the batch-map. In fact, this causes the source to prematurely resume the transmission of the rest of the batch, leading to a more significant number of collisions.

- An interesting observation in Figs. 13d and 13e is that the results of ETX are unexpectedly better than those of EAX. The reason for the difference is that the proximity of the forwarding nodes (i.e., forwarding contribution redundancy) makes the potential superiority of the multi-path consideration of EAX irrelevant.

To investigate how the performance ratings of different metrics vary with differing OR protocols, we compare the delay results of the topology scenario of Fig. 13e for the EXOR and MORE protocols.

MORE, a MAC-independent opportunistic routing protocol, is one of the most-cited OR protocols. The excellent performance of MORE is due to the fact that MORE solves the coordination (scheduling) problem between forwarder nodes with the introduction of the concept of transmission credit, and addresses the problem of duplicate transmissions by forwarder nodes through NC employment and makes the use of intermediate ACKs unnecessary (the latter is taken care of by transmitting batch-map in EXOR). MORE inherently uses the ETX metric for its credit calculation. We need to discuss MORE’s credit accumulation and consumption mechanisms more closely to incorporate EAX and EPA into MORE.

In MORE, \( z(i, dst) \) is defined as the expected number of transmission attempts node \( i \) should make to deliver one packet to \( dst \):

\[
z(i, dst) = \sum_{j \in C_i} \frac{P(i, j) z(j, dst)}{P_{C_i}} .
\]

For each forwarding node \( i \), \( TXcredit_i \) is defined as the number of transmissions that \( i \) should make to the final
destination upon successful reception of an innovative (new linearly independent) coded packet from a forwarding node with a higher ETX. Each successful reception increases the transmission credit of \(i\) by \(TXcredit\):

\[
TXcredit_i = \frac{z(i,d)}{\sum_{j \neq i} z(j,d)p_{ij}}. \tag{117}
\]

On the other hand, every transmission attempt by \(i\) decreases its transmission credit by 1. MORE prunes the low-quality forwarding nodes with \(z(i, dst) < \frac{1}{10} \sum_i z(i, dst)\).

To serve our comparison purpose, we replace \(z(i, dst)\) in the credit calculation of eq. (117) with ETX, EAX, and EPA one at a time. For instance, \(TXcredit_i\) for the EPA case would be \(\sum_{j \neq i} EPA(j,d)\), where the numerator denotes the expected progress of a forwarded packet by \(i\), and the denominator is the total progress contribution of \(i\) in terms of the forwarded packet.

The simulation environment, setup, and parameters used for MORE are the same as those used for EXOR. The side-by-side simulation results of both protocols employing the three OR metrics (ETX, EAX, and EPA) in the topology scenario of Fig. 13-e are illustrated in Fig. 15. MORE clearly achieves its best result using EPA, whereas EXOR favors ETX for this specific topology scenario.

In this section, we demonstrated how the network performance (total delivery delay) is impacted by choice of OR protocol, OR metric, and the topology scenario.

### F. OR Metrics: A Scrutiny

A closer and critical look at the OR metrics reveals some serious issues that are worth discussing in detail. We have divided these issues into two groups: conceptual pitfalls related to fundamental missed ideas in the general approach to OR metrics and overlooked details related to the definition of some specific OR metrics (Fig. 16).

1) **Conceptual Pitfalls:** In this subsection, we raise some general concerns about how OR metrics are computed.

- **OR Metric-Computation Directionality:** Most of the metrics are calculated from the destination to the source. In other words, the metric rates a node based on the cost of delivering a packet from that node to the destination. This value is then used to prioritize this particular node amongst all other members of the same hyperarc receiving the packet. The general problem with this approach is that the quality of the incoming links is not accounted for in the process of prioritization, which might degrade the OR performance to worse than that provided by traditional routing. To illustrate this issue, consider the network of Fig. 17. All the intermediate nodes have small differences in their outgoing link qualities to the destination. A typical OR protocol prefers \(A, B,\) and \(C\) over \(D\) according to any link-quality-based OR metric (e.g., ETX), whereas \(D\) is clearly the best forwarding node. All the packets received by nodes \(A, B,\) and \(C\) combined would most likely be received by node \(D\) as well. In other words, an accumulation of packets in \(D\) occurs due to its incoming high-quality link. Furthermore, according to the link probabilities in Fig. 17, these packets have almost the same chance of reception by \(dst\) if \(D\) rather than the others transmit them. Therefore, unnecessary transmission attempts by \(A, B,\) and \(C\) can be prevented by letting \(D\) transmit first. To investigate the above, we simulated the network in Fig. 17 under the EXOR protocol for two cases: ETX-based node prioritization (A-B-C-D) and manipulated node prioritization (D-A-B-C). The total delivery delay results are shown in Fig. 18. The results confirm that by looking only forward, the OR metrics miss the reality.

The conclusion we are attempting to make is that by introducing new metrics that also consider the quality of how error-free incoming packets feed a forwarding node, the OR performance can be improved beyond the levels achieved by the classic metrics. However, the
measurement of a node’s feed quality may not always be straightforward. For instance, in multi-hop scenarios, the traffic descends on an intermediate node from different paths (Fig. 19).

Fig. 17: Backward-only metric evaluation problem: the metric prefers A over B, B over C, and C over D. However, the forwarding order should be exactly reversed to achieve better performance.

Fig. 18: The performance results of applying EXOR to the topology scenario in Fig. 17 using ETX and manipulated prioritization.

Fig. 19: While classic metrics calculate the quality of delivery at the destination from an intermediate node i, the importance of the quality of packet reception at i is ignored.

- **ACK Scope Impact:** In the OR metrics that consider the calculation of the expected number of transmissions required, an important issue is the way in which a subject packet is acknowledged in the corresponding parent OR protocol. In Fig. 20, where \( p_1 \) and \( p_2 \) denote the delivery probabilities to and from an intermediate node i, if the packets from the source to the destination are verified on a per-link manner (i.e., store-process-forward), the required expected number of transmissions is equal to \( \frac{1}{p_1} + \frac{1}{p_2} \). However, in an end-to-end verified case, since the intermediate node has to wait until the completion of the transit packet (i.e., store-forward), the expected number of transmissions required is equal to \( \frac{2}{p_1 + p_2} \), which is greater or at least equal to \( \frac{1}{p_1} + \frac{1}{p_2} \). The expected number of transmissions required can be equal to \( \frac{1}{p_1 + p_2} \) only in cut-through wired networks. Interested researchers are cautioned about any confusion regarding this issue.

Fig. 20: A simple two-hop src – dst network transmission.

- **Links’ Order Impact:** Another critical issue, which was initially raised by [238], is the impact of the links’ order. [238] states that if the MAC layer’s transmission-attempt limit is considered, then the location of the low-quality link on the path is an important characteristic. A first glance at Fig. 21 might lead to the conclusion that, in terms of link quality, the transmission costs of delivering one packet through both paths are equal. However, if the MAC layer’s transmission-attempt limit is 2, then packet delivery over the upper path costs 20 transmissions while it costs 18 transmissions over the lower path. Additionally, the above is valid if per-link verification (link-layer acknowledgment) is used.

Fig. 21: Two similar paths with different link orders.

2) **Overlooked Metric-specific Details:** Throughout this subsection, we identify details that have been overlooked in the computation of specific OR metrics.

- **ETX:** According to [104], if the forward and reverse delivery ratios of a link are \( d_f \) and \( d_r \), respectively (Fig. 22), then:

\[
ETX = \frac{1}{d_f d_r},
\]

which is understood to be valid for per-link acknowledgment scenarios. However, since packets should be received correctly before being acknowledged (store-process-acknowledge) and since the packet and its ACK substantially differ in length, the correct average number of transmissions, in terms of the forwarding packet transmissions, should be:

\[
\frac{1}{d_f} + \frac{L_{ACK}}{d_r}.
\]
How this error could affect the final results depends on the numerical values of \( d_f \), \( d_r \), and \( L_{\text{ER}} \).

- **ETC**: In an attempt to determine ETC, [137] calculates \( FAR \), the wake-up ratio of all the forwarding candidates, by finding the union of all the wake-up periods (eq. (2) in [137]). There appears to be an error in this derivation since the union of all the wake-up periods requires additional terms according to eq. (120) (beyond the second term):

\[
|\bigcup_{i=1}^{n} A_i| = \sum_{i=1}^{n} |A_i| - \sum_{1 \leq i < j \leq n} (|A_i \cap A_j|) + \ldots + \sum_{1 \leq i < j < k \leq n} |A_i \cap A_j \cap A_k| - \ldots + (-1)^{n-1}|A_1 \cap \ldots \cap A_n|
\]

(120)

which might be significant.

- **EPA/EOT/EAR/EDRb/DDR/MEAR/OEE/DUER/FE/espeed**: Distance proximity might not always be an appropriate packet advancement criterion since a geographically closer-to-destination node might have no forwarding path. For instance, in the network of Fig. 23, all the nodes on the upper path are geographically closer to the destination than node 2 on the lower path, but the upper path is a communication dead-end.

- **ETCoP**: [139] raises a link order issue similar to that mentioned previously in this section, though without relying on the MAC layer’s transmission attempt limit (see Fig. 20). Furthermore, [139] states that a packet originating from \( \text{src} \) and destined for \( \text{dst} \) in Fig. 20 can experience only the following (in a per-link verification scenario):

- the data packet may be dropped on the first link (with probability \( 1 - p_1 \)),
- the data packet may be successfully delivered on the first link and be dropped on the second link (with probability \( p_1 (1 - p_2) \)),
- the data packet is successfully delivered on both links (with probability \( p_1 p_2 \)).

The total expected number of transmissions is \( (1 - p_1) + 2p_1 (1 - p_2) + p_1 p_2 \). With a similar extension, [139] estimates the expected number of transmissions of an n-hop path under the failed receptions of the end node, \( F(n) \), from which ETCoP is calculated as in eq. (16) in [139].

We have to dispute the two-link derivation of the total expected number of transmissions above if no additional constraint is imposed since the packet could theoretically experience an unlimited number of failures on the first link before getting through. In other words, we believe that the sample space of possible outcomes of packet experience in [139] is not complete. The exact expectation, accounting for all the possible packet experiences, should be:

\[
\sum_{m=0}^{\infty} \left( \sum_{n=0}^{\infty} (1 - p_1)^m p_1 (1 - p_2)^n p_2 (m + n + 2) \right),
\]

(121)

which simplifies to the familiar expression of \( \frac{1}{p_1} + \frac{1}{p_2} \).

The latter shows that without any additional constraint (e.g., as in [238]) and in a per-link verification scenario, the link order does not matter, as it was concluded in our earlier discussion.

- **EATT/OETT/MEATT/EAD/EOT/OEE/FE**: In the definition of this group of metrics, we observe the co-presence of the packet length and the probability delivery ratio parameters. This co-presence may undermine the generally agreed-upon concept of inter-dependency between these two parameters presented by, for instance, the classic independent-bit-errors model of:

\[
P_{\text{PKT}} = (1 - p_b)^L,
\]

(122)

where \( p_b \) and \( P_{\text{PKT}} \) denote the bit error and packet error probabilities or some other empirically obtained relationship, as in [239].

- **STR**: Regarding the network of Fig. 1 in [121], we were not able to generate the same results as in Table I.

**IV. OR Metric: Future Works**

Simply speaking, the OR is transmission scheduling among a CFS selected based on some OR metrics, in multi-hop networks. Thus, the metric design significantly affects the network’s throughput. Fast-paced emergence of either new network types or new applications on existing networks, following the growth in 5G, Smart City, and IoT technologies, necessitates the development of new OR metrics which reflect the new environments and generate adequate performance. The multi-faceted nature of the OR metric requires a structured approach to its development process. Figure 24 proposes a...
Fig. 24: Future research suggestions framework.

development framework, consistent with the OR metric design process of Fig. 6 in which:

- the development is divided into two main fronts, parameters, and formulations,
- the time-evolution of the research focus has been demonstrated,
- and for each constituent, the level of research activity is illustrated by different color shades wherein darker shades represent higher activities.

A. Parameters Development:

Devising OR metrics with new parameters, in a systematically manner, can be considered in three different levels, the network, node, and link levels (the magnified part of Fig. 24).

- Network-level parameters:
  Some example network-level parameters for future exploration are as follows:
  - Network Type (platform): Emergence of new types of network or new missions (applications) in existing networks, for instance VENs [4], Internet of Vehicles (IoV) [240, 241], 5G [242], UAVNET [5, 7], molecular communications [243], and D2D [10, 11, 244], have introduced new parameters describing the specific aspects of their corresponding networks or missions.

  Devising OR metrics, which are aware of these parameters, helps to achieve better routing performance. For example, while OR was originally designed for WMNs featuring static and under-single-administration topology, nowadays, it has found its way in highly dynamic networks such as VANETs and UAVNETs. In these environments, the metric should adequately reflect the impact of high node mobility on the wireless link quality.

- Degree/Integrity of Cooperation: With very few exceptions, almost all the OR proposals assume that the transmission-overhearing nodes participate in the forwarding process willingly, trustfully, and indiscriminately. The variety of new emerging wireless applications demands wireless networks with different missions and organizations. While OR was originally designed for WMNs featuring a fixed and predetermined organization, usually under a single administration, OR can now be deployed in structurally relaxed (ad hoc) networks. In such circumstances, exposure to security lapses and selfishness might impact the integrity and the degree of cooperation in OR. A metric aware of the degree/integrity of cooperation will result in better CFS selections in less-friendly scenarios.

- Trust: The concept of trust has prevalently been used to differentiate between the goodwill of nodes. Trust is defined as a node’s degree of subjective belief about the future behavior of other entities in the network in a given context [245, 246, 247]. In the context of OR, trust can be considered to be the level of reliance on (cooperation of) a node to forward a packet if it is required to do so as a member of a CFS. Different trust computational approaches have been introduced as different trust models. Our study shows that E2TX [52], RTOR [180] and its close relatives, TORDP and GEOTOR [181], are metrics that accommodate trust via a very simple direct trust model. ETOR [33] extends the trust model to include indirect trust. However, all the aforementioned trust-based metrics act on a link level. We believe that there is ample room for research exploring more involved trust models acting over a larger scope, such as a path rather than just a link.

On another front, nodes might not contribute equally to the OR in networks that are not under a single administration. For example, a node might prioritize its self-generated traffic or a specific flow over other transit ones.

- Topology: Concerning the effect of the topology-OR metric pair on the network’s performance, extensive simulations in section III-E revealed implicit dependencies. In the same manner, it is evident that the node density impacts the size and quality of CFS. Also, end-to-end metrics perform better in dense networks, while per-hop metrics are generally better suited to sparse networks — all of the above points to the importance of topology in OR problems. As a consequence, further topology-aware metric studies are encouraged.
Node-/Link-level parameters:

Regarding the node- and link-level considerations, one can divide the packet delivery process into pre-transmission (preparation), transmission, and propagation phases.

The pre-transmission phase constitutes all the processes that occur to get a packet to the head of a sender node’s transmission queue. These processes are exclusively internal to the sender node (node-level-only considerations).

The transmission phase includes the selection of the transmission parameters (e.g., transmission power, transmission rate/channel), which, on the one hand, requires the sender node’s corresponding capabilities, and on the other hand, impacts the packet delivery quality on the forwarding link(s) (joint node-/link-level considerations).

Also, in the propagation phase, the parameters of the physical channel (path loss, shadowing, multi-path fading, etc.), as link-level-only considerations, contribute to the packet delivery quality.

In the following, we present some suggestions for future research on node-/link-level parameters.

– Packet size: As mentioned in Section III-F, experimental results (e.g., [248]) and mathematical models (e.g., equation packet length) relate the PDP, the core parameter in OR metrics, to the packet size and the condition of the wireless channel [239]. While shorter packets result in higher PDPs, the network goodput deteriorates due to the additional overhead of the packets.

According to the best of our knowledge, almost all previous OR metric research assumed a fixed packet size. We believe that answering questions similar to the following might open promising research avenues: What is the best packet size for achieving an optimum OR throughput in a given network topology? Is it beneficial to use multiple simultaneous packet sizes in a single OR flow? How does, if at all, variable packet sizes help in dealing with long-term network dynamics?

– Intra-node considerations: OR metrics are traditionally more concerned with link-quality issues (exterior to node) than forwarding capabilities and the internal processes of the involved nodes. We would like to address the intra-node phenomena that impact the forwarding capabilities of the nodes in the OR context.

With the main focus being on the packet retransmission limit in the context of WSNs, [249] discusses the internal processes involved from the reception of a packet until the transmission of the packet. Similarly, we model a forwarding node as the succession of a receiver, an input queue, a processing entity, an output queue, and a transmitter, as illustrated in Fig. 25. In single-radio scenarios, reception and transmission share common circuitry.

The forwarding capability of a node in OR is strongly related to the dwelling time of the packet in the succession of the input queue, processing entity, and output queue (pre-transmission phase in Fig. 25). While the processing power (hardware/software) is inherent to the node, the length of the queues is dependent not only on the node’s processing power but also on the node’s involvement in the underlying network transactions. Low processing power (either because of the hardware limitations, or the complexity at the overlaying OR/higher-layer protocols) can delay the transportation of packets from the input to the output. Moreover, a node located along a succession (or at the intersection) of good-quality links is more likely to be repeatedly selected as a forwarding relay, which will result in crowded queues (i.e., congestion) or packet drops due to limited queue lengths. Figure 26 illustrates a circumstance where the classic OR prioritization of the nodes on the top path over those on the lower path (higher link qualities) does not necessarily result in better performance. Therefore, the development of new OR metrics that also reflect the intra-node capabilities/limitations (e.g., [38] considers the output queue length), is worth additional research effort.

– Network Coding: OR and NC both attempt to reduce the number of required transmissions, the former through diversity over links and the latter through diversity over transmissions. An interesting potential research topic is to investigate how the introduction of coding-aware metrics, as opposed to already studied joint coding-OR techniques using non-coding aware
metrics [23], affects the OR's total performance. Thus far, the only related work is the FE metric [165].

- **Link Correlation**: Link correlation, defined as the channel similarities between multiple receivers and one single data source, has been addressed in several works [250] [251]. Link correlation results in the receptions at multiple receivers listening to the same transmission being dependent. On the other hand, OR, by its very nature, deploys the diversity over multiple links for more efficient delivery. Therefore, OR is more promising when links are independent and capable of incremental cooperation. The impact of link correlation on the OR performance has been studied in [127]–[131]. Furthermore, a simple method for estimating link correlations is presented in [250]. cEAX [129] has introduced the impact of link correlation on the $F_1$ selection mechanism in EAX [111], [112], enforcing an additional constraint on the size of $F_1$. The authors in [128] have suggested using the packet loss joint probability among all the forwarders in the same level when listening to a sender from the previous level. Link-correlation-aware OR metrics increase network throughput by avoiding reception redundancy among highly correlated links. We believe that there remains room for further study on this topic mainly because:

  * the link correlation is the most counter-effective factor in the OR performance,
  * the traditional link correlation computations rely on statistical operations on long streams of data rendering it impractical for heavily fluid wireless networks such as UAVs and VANETs,
  * to the best of our knowledge, the link correlation in recently-popular directional antenna scenarios is not addressed yet.

- **Link symmetry**: In almost all the previous OR-related studies, links (the PDP) are considered to be symmetrical. First, physical transmission paths in wireless channels are not necessarily reversible in terms of PDP. Second, since packets of different sizes (e.g., data packet vs. acknowledgment packet) flow in different directions over a link, considering earlier discussions, the assumption of symmetrical links (equal PDPs) may not be accurate.

**Direction awareness**: OR and directional wireless transmission are intended to improve efficiency by, to some extent, contradicting strategies. OR attempts to benefit from the inherent broadcast nature of the wireless transmission by getting all the overhearing nodes to cooperate in furthering a flow. However, directional transmission attempts to let multiple independent flows exist concurrently by limiting the mutual interference between them (i.e., fewer nodes involved in furthering a specific flow). From another perspective, the optimization scope of OR includes a single flow, whereas the optimization scope of directional transmission is the entire network.

To clarify the potential compromise between the two approaches, we show two source-destination pairs with overlapping wireless space in Fig. 27. When employing the conventional omni-directional OR, the two transmissions should occur in tandem since src2 overhears src1’s transmission, and, to the benefit of the first flow, src2 can potentially serve as a member of src1’s CFS. On the other hand, when using the directional-OR configured as illustrated, src2 cannot hear src1’s transmission and, to the benefit of the total throughput, it can initiate its own flow concurrently.

In somewhat related efforts, [253] applies beamforming to enhance performance in a single-flow scenario by concentrating the transmission power on those members of the CFS with a higher packet progress contribution. [253] tries to limit the number of involved forwarding nodes without any reference to how this limitation will affect other possible concurrent flows. With the increasing popularity of directional wireless transmission, particularly in new generations of wireless networks (e.g., 5G [12]), incorporating these two otherwise-contradicting approaches through introducing direction-aware OR metrics is promising.

- **Dynamic transmission power**: The transmission power of a wireless node directly influences its radio range. Manipulating the transmission power impacts the quality of the surrounding links, thereby resulting in a change in the connectivity of the network through eliminating existing links or creating new links (logical topology change). Therefore, the radio range directly impacts the routing paradigm.

In traditional routing, short and high-quality links are preferred over long and erroneous wireless links [104] due to the nonlinear relationship between power and distance in wireless transmission. However, due to the multi-path nature of OR (where even low-quality links are contributing), this preference cannot be extended to OR scenarios without reservations. From another
perspective, any change in the connectivity paradigm and/or link qualities will likely impact the values of the OR metrics and, consequently, the forwarder candidate selection results.

Therefore, incorporating the transmission power into the OR metrics (provided that the variable transmission power is supported at the PHY layer) and investigating the interaction between the transmission power and the underlying OR performance may reveal new interesting research problems.

- **Radio multiplicity:** While imposing higher costs on hardware, OR in networks with multiple-radio transceivers can benefit from an extra degree of concurrency, provided that the multi-radio support of the embedded metric is in place.

**B. Formulation Development**

The formulation of an OR metric shows how its parameters interact and is a direct result of the adopted design optimization process as per Fig. 6. Traditionally, the majority of the optimization processes have been mathematical-, heuristics-, and empirical-based. As time goes by, wireless communications, particularly under 5G and IoT umbrellas, like other fields of engineering, face the challenge of data hugeness. Because of this, and also because of the advances in computing power, Machine Learning (ML) (and more recently Deep Learning (DL)) methods have found their ways into different parts of wireless communication systems. While there are several ML-/DL-based wireless routing works in the literature, to the best of our knowledge, there are not so many (if any at all) such research efforts regarding OR metrics.

About OR metric objectives, moving towards more complex networks requires the merits of the relaying nodes to be a compromise between more than one not-necessarily-congruent basic objectives. A new research direction can involve devising hybrid metrics as either a function of multiple single-objective metrics or a single multi-objective metric. Conventional wireless networks are homogeneous in type and limited in size. Thus, it is practical to define a single OR metric (i.e., global OR metric) for the whole network and disseminate the metric information during a reasonable time duration. Modern wireless networks are characterized by the high number of short-range nodes (i.e., large size in terms of the number of hops), e.g., in the context of IoT, as well as by the coexistence and cooperation of different-in-nature networks (i.e., heterogeneous networks), e.g., in the context of 5G. In such networks, a single OR metric cannot adequately reflect differing coexisting natures in the network. An attractive research avenue can include an investigation into designing a set of local OR metrics each representing a particular homogeneous neighborhood, in the case of heterogeneous networks, or a specific limited-in-size cluster, in the case of large-scale homogeneous networks.

We conclude this section by expressing the serious need for rethinking the computation directionality of OR metrics, as discussed in section III-F.

**V. Conclusion**

The ubiquity of multi-hop ad hoc wireless networks, both new and emerging or classic ones, necessitates greater efficacy in wireless routing algorithms. In this regard, OR, which has proven its merits for more than a decade, remains promising. At the heart of each OR protocol is an embedded OR metric that influences the overall performance. In this work, we start with a tutorial on OR wherein it is studied from a new layered-diversity point of view, and a new OR metric design scheme is introduced. Then, an exhaustive treatment of OR metrics, classified based on their computation methods and scopes and reformulated according to a unified notation, is presented. The latter enables us to take a structured, investigative, and comparative approach to OR metrics, which provides valuable insight for interested researchers. Extensive simulations compare the main representatives of OR metric classes and reveal not-so-obvious dependencies regarding the network performance. Self-explanatory, easy-to-grasp, and visual-friendly quick references are provided, which can be used independently from the rest of the paper. Finally, a new insightful framework for future research directions, consistent with the introduced OR metric design scheme, is developed. We can confidently claim that this tutorial survey is the first complete and exclusive investigation on OR metrics, beneficial to both generalists and OR specialists.

![Fig. 28: The path(s) selected when using three different routing protocols: the best next-hop, the shortest single-path, and the best any-path OR based on EAX.](image)

**VI. Appendix**

To obtain a better understanding of how OR differs from traditional routing protocols, Fig. 28 gives an example differentiating between the paths traversed from a source \((src)\) to a destination \((dst)\) using the best next-hop, the shortest single-path, and the best any-path OR protocols. The numbers on the connecting links denote the corresponding delivery probabilities. The best next-hop protocol suggests the path \(src-C-dst\). The shortest single-path protocol (i.e., Dijkstra) selects the path \(src-B-D-dst\). Based on the EAX metric, values shown below each node’s name (to be detailed shortly) in Fig. 28 the OR protocol suggests the ordered list of forwarding nodes \((dst, D, E, A, B, C, src)\), represented by green numbers above each node.
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