Reliability Tradeoffs for Energy Efficient Wireless Networks

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Abstract—A complex wireless deployment under realistic scenario is prone to failures and it becomes very hard to determine when to stop retransmitting a message in order to ensure proper delivery. In this paper, a simple effective link-attribute estimator is proposed that is capable of identifying the quality of communication between neighboring mobile devices while maintaining the scalability. By relying on our link-quality estimator, a maximum number of attempts is computed which (probabilistically) ensures the message delivery while maintaining energy-efficiency. Through appropriate adjustments, our estimator is capable of obtaining the bounds on the number of retransmission attempts required to increase the message delivery ratio. This enables wireless devices to establish a threshold on the number of transmission attempts, thereby avoiding those retransmissions that would only result in wasted energy. Such dynamic threshold helps enforce at least a minimum number of transmission. Simulations prove the effectiveness of our LQ estimator with respect to energy efficiency and message delivery reliability. Results indicate that an acceptable message delivery ratio can be maintained while increasing the overall energy efficiency.

Index Terms—Energy Efficiency, Link Quality, Reliability.

I. INTRODUCTION

Next generation of wireless networks are being projected to possess multiple heterogeneous wireless access technologies. Their coexistence would complement end-users in simultaneously connecting to different access technologies with varying underlying characteristics [1]. With powerful hand-held mobile smartphones, this reality seems sooner than later. However, battery technologies have not improved at the same rate as the link capacity, leading to an exponentially increasing gap between energy requirements and available battery capacity [2]. In a recent report [3], radio access and message transmissions have been shown to account for energy usage between 50% – 70% of the total resources. Furthermore, power consumption of commercial 802.11 transceivers (in all operating modes except sleep) has been increasing with each new standard [4].

Considering the adoption of heterogeneous networks in mesh scenarios [5] and cellular network deployments, and increased thrust for long-distance communication, power consumption is expected to be even higher in the transmit mode. In the meantime, energy consumption of wireless networks have been directly linked to an increase in the greenhouse gas emission [6]. This has led to two contradicting requirements: high capacity wireless traffic and the need for energy conservation.

The trend toward highly energy efficient wireless networks has encouraged to look at innovative solutions that are capable of providing a trade-off between the Spectrum Efficiency (SE) and the Energy Efficiency (EE), i.e., given available link capacity and bandwidth, balance the achievable throughput rate and the energy consumption of the system [6]. However, the SE-EE relation is not so simple, and as shown in [6] circuit power break the monotonic relation, in practical systems.

Other factors such as transmission distance, selected coding mechanism, modulation, channel selection, and frequency selectivity algorithms etc., have a significant impact on the SE-EE trade-offs. To make matters worse, existing literature mainly focus on simplified scenarios with limited interference, single-user networks and single channel, instead of a realistic and a complex network scenario. Miao et al. [2] concluded that even if the global optimal power allocation solution could be found, it would be impractical to a user as it would require a complete network knowledge, including the level of channel interference.

A simple naive solution is to transmit as little as possible. By selective transmission, energy efficiency could be clearly increased. But, limiting the transmission may lead to a reliability problem since it might fail to correctly deliver messages. For optimal performance, there are different ways to approach this. For example, one could consider available energy, packet transmission delays, traffic rate, node density as well as other parameters, and define a single functional metric.

Another simpler way is to establish an accurate Link-Quality (LQ) estimator so that devices can have a thorough knowledge about their adjacent neighbors [7]. Higher quality links will result in a smaller number of dropped packets and fewer retransmission attempts, and this is the approach we address in this paper. Defining this estimator ought to be feasible regardless of time-variant behavior of the wireless channel, as well as other factors such as multi-path propagation and pre-existing obstacles.

Unlike previous works, we propose to study not the correlation between SE-EE, but rather the LQ-EE relationship. We base our analysis on the work of Couto [8], but extend it to include nodes within two-hops, thereby providing a simple but effective link-quality estimator which can be used to sig-
nificantly limit the number of retransmission attempts on low-quality links. This leads to an increase in the energy efficiency, while still maintaining an acceptable message delivery ratio.

As a proof-of-concept, we study network-wide broadcasting which is one of the fundamental group communication primitives for various services in a distributed system. It is a complex operation, that does not scale well as the system grows [9]. We also consider a realistic omission fault model capable of representing real-world scenarios where link failures, network partitioning, topology changes, and momentary node failures frequently occur.

Our motivation is to identify an estimator capable of not only dealing with omission faults, but that can also handle scalability. It may be noted that when devices behave asynchronously, network-wide reliable broadcasting cannot be guaranteed, even if only one of the devices is allowed to crash [10]. For this reason, it only makes sense that in a realistic deployment where nodes might not be aware of every single functional device in the network and where devices may fail, we rely only on the local perception that the mobile device has and not on the global information nor on any specific model of it’s behavior. So, through simple piggy-backing and with no additional communication cost, nodes can relatively easily detect all neighbors lying within a radius of two-hops.

Our estimator calculates the Expected Number of Transmission Attempts (or simply “ETA”) that is needed to reliably send a broadcast message to these neighbors. Through constant updates, our estimator is capable of calculating the upper and lower bounds on the number of retransmission attempts required to increase the message delivery ratio. In order to evaluate our link-quality estimator, simulations are compared and energy efficiency is calculated based on the number of retransmission attempts, while also showing the impact of message delivery on the reliability.

The paper is organized as follows. In Section II we present our ETA approach both through the analytical model, and a practical example. In Section III we show the effectiveness of ETA approach in terms of reliability and expected number of retransmission, in two different network topologies. Finally, conclusions are drawn in Section IV.

II. OUR CONTRIBUTIONS

A number of papers have proposed approaches that ensure higher delivery rates for broadcasting in the wireless networks [11–13]. However, many of them do not consider a real world scenario characterized by the interference introduced by the environment, link instability, and transmission failures [14–16]. Few solutions are scalable, as they require that the number of devices participating in the network be fixed [17–20]. While other solutions require specialized hardware such as GPS receivers, multiple antennas, or even the support of fixed gateways. We believe this needs to be reexamined.

It is generally accepted that a successful protocol needs to combine different approaches in order to achieve a higher delivery rate [15, 21]. Combined strategies often include forward error correction encoding, link-quality estimation, and retransmission [22–27]. Unfortunately a small number of existing protocols accurately reflects how little attention has been devoted to the reliability requirements beyond the “best-effort” while broadcasting in a wireless network [28]. Protocols based on forward error correction encoding algorithms require that the sender add redundant data to each message. This enables receivers to detect and correct errors without any need for additional sender data. As long as a sufficient number of messages are received, the receiver can re-assemble and correct compromised data messages. The link-quality estimation concept utilizes the idea of finding neighboring links through which message forwarding tends to suffer smaller mid-conversation failures, collisions, drop rates and many of the other problems that are inherent in wireless communication. By applying this concept, mobile devices are able to subjectively measure the neighbors and choose the ones that can maintain a high quality communication link. Thus, instead of randomly choosing a link, those that could persist for a certain minimum period are preferred. Therefore, devices are (probabilistically) ensured of the message delivery. However, estimating a link-quality is not a trivial task.

Finally, retransmission-based approaches are based on an easily understood concept: whenever a message is sent, a copy is retained until all the receivers acknowledge its correct reception. If no acknowledgement is received within a reasonable time, the sender will retransmit the same message until it can be assured that all the devices have received the message, excluding those devices that have failed or left the network.

A link-quality estimation algorithm attributes a value to the links based on logical or physical metrics. As the name implies, that physical metrics depend on the radio hardware, and can include the Received Signal Strength Indication (RSSI), the Link-Quality Indication (LQI), or the Signal-to-Noise Ratio (SNR). However, these are dependent on the hardware, while RSSI is often continuously measured, the LQI is only available on successfully exchanged received messages, and not when there is a link failure or a packet loss. Logical metrics are independent of the hardware, and normally keep track of the packet success rate. Most are calculated with an exponentially weighted moving average [29]. In order to improve the accuracy, hybrid link-quality estimators combine these two approaches [30]. Surprisingly, a very limited number of broadcasting protocols use any kind of reliability information of its neighbors in order to select a better forwarding neighbor [26, 27]. This can possibly be justified by the fact that all known link reliability-based protocols depend on the age of the link. These works consider a long-lived route to remain valid without losing the connectivity over time. What is implicitly assumed that certain devices group after a while, and thereafter remain moving in a relative direction and with the same relative speed, while new links always tend to be transient. However, according to [31], these assumptions can be justified only for a few dynamic scenarios and not much can be presumed regarding movement of two mobile devices that just came into one another’s transmission range. Clearly, the duration of a link largely depends on the movement of the
nodes. In fact, depending on the mobility pattern, old links need not necessarily be more stable than the new ones.

We propose a combination of both (i) the retransmission and (ii) the link-quality estimator strategies. This results in a reliable link-quality estimator that would pick higher quality links during retransmission attempts. However, it is a common-sense for users to be not necessarily interested in how long a link might live, but rather to find whether or not the link is available at that time. Therefore, we consider the recent behavior of the forwarding nodes responsible for retransmitting the message as a link-quality measure. Also, in order to guarantee scalability, retransmissions will be fixed based only on the local neighborhood replies: nodes will only retransmit a message if neighbors up to \( k \)-hops did not receive it, where \( k \) has been assumed to be 2. Additionally, by relaxing the assumptions on the network stability and device connectivity, it becomes very hard to determine when to stop retransmitting in order to ensure proper delivery. By relying on our link-quality estimator, a maximum number of attempts is made (probabilistically) ensures delivery while minimizing energy usage.

In the following, we introduce our energy model and the ETA estimator, also described through a practical example.

**Energy Model**

We assume that devices transmit data with fixed transmission power, and receive it at a fixed reception power. Power consumption is then independent of the transmission distance between neighboring devices. Similar to [32], we adopt the following energy model to calculate the power consumption:

\[
p \approx e(b_r + b_t),
\]

where \( p \) denotes the total energy consumption of a device receiving \( b_r \) bits and transmitting \( b_t \) bits, and \( e \) indicates the energy consumption per bit at the receiver circuit. However, instead of overly complicating our analysis, in this work, our goal is to reduce unnecessary message transmissions, which will reduce the overall \( p \) consumed.

**ETA Estimator**

Our ETA estimator determines the expected number of transmission attempts required to ensure the message delivery, and to a certain extent, the expected link-quality for future transmissions. This approach can guarantee an effective message delivery in IEEE 802.11 networks which do not consider this aspect.

Through the use of the expected link-quality between neighbors, we obtain a probabilistic upper and a lower bound to classify the reliability of neighbors. For each hop between a two neighboring nodes, we can measure the Packet Loss Probability (PLP) at both sides (i.e., \( p_d \) and \( p_u \) as downlink and uplink PLP, respectively), and then we are able to calculate the expected number of retransmissions. Since IEEE 802.11 protocol requires that packets be acknowledged, we can denote the probability of unsuccessful transmission \(^1\) from one node to the other in the \( k \)-th hop, as:

\[
s_k = 1 - (1 - p_u)^k(1 - p_d)^k.  \tag{2}
\]

We assume that the probability of a successful transmission of a given packet is independent of its size and is also an independent and identically distributed variable (i.i.d). This is modeled by a geometric distributed random variable, and the number of expected transmission attempts can be calculated as:

\[
ETA = E[n] = \sum_{n=0}^{\infty} n\pi_n = \sum_{n=0}^{\infty} n(1 - s)^{n-1} = \frac{1}{1 - s}. \tag{3}
\]

While this may not be realistic in a real wireless deployment, it is good for deriving analytical bounds. By this, we accept the fact that there are many other factors, such as interference as well as the backoff algorithm of every retransmission attempts that we omitted in our model. We argue that even if we are able to model every single possible parameter, many underlying assumption may not completely hold in a real-world deployment. Therefore, in the worst case, calculating pessimistic upper and lower bounds will detect the action resulting in smaller number of retransmissions, thereby saving energy. This is a trade-off that most network designers are comfortable with.

The upper bound can be calculated considering the message transmission for the \( k \)-th hop. Let us assume \( k = 2 \) hops (to allow for scalability). Considering acknowledgements coming from neighboring nodes, relation (2) becomes:

\[
s_2 = 1 - (1 - p_u)^2(1 - p_d)^2.  \tag{4}
\]

In a practical scenario, obtaining exact values for \( p_u \) and \( p_d \) is quite difficult to identify due to many factors that influence and impact the quality of wireless transmissions. In the IEEE 802.11 standard, adaptive rate control algorithm has been employed, which affects the reliability and apply a more robust modulation scheme (and a corresponding lower bit rate) as the link quality deteriorates.

Our solution aims to use the number of retransmission attempts from the previous transmissions as a guideline and can be used to obtain a calculated guess of the PLP. Our main contribution is to determine a threshold to limit the number of retransmission attempts. Adaptive rate control algorithms can still be used, and it only increases the message delivery ratios.

**Practical Example**

In order to simplify understanding but without lack of generality, we assume that \( p_u = p_d \), which means that the packet loss probability from and to the sender is assumed the same. This may not be true in practice, but the aim is

\(^1\)In this paper, we use the term of unsuccessful transmission, as well as transmission failure probability, indifferently.
just to give a practical example of our approach. Equation (2) becomes:

\[ s_k = 1 - (1 - p_u)^{2k}. \]  

(5)

Let us assume that a device has required 4 retransmissions attempts (i.e., \( ETA = 4 \)), before receiving an acknowledgement from a neighboring node. Figure 1 shows the \( ETA \) values versus the PLP for one- and two-hop neighbors, as well as the analytical trends. The value of \( ETA = 4 \) is obtained for PLP in the range from 42.5% up to 50%. This produces (i) a lower bound on the number of future attempts in order to ensure a reliable delivery of the next message, and (ii) an upper bound on the maximum number of retransmission attempts before assuming that one-hop node has failed. This translates to a range between 10 and 16 attempts. With this information, the device knows the maximum number of attempts on the next round of message forwarding to two-hop nodes.

III. Simulation Results

In order to validate the LQ-EE trade-off in our proposed link-quality estimator, a large variety of simulation experiments has been performed using a wide range of different parameter values. In this section, we show some representative results on the performance of ETA approach. Our simulation is divided into two sets, which assume respectively (i) the generation of a random network topology, and (ii) a regular (evenly distributed) grid topology with a fixed average node density.

For a fixed number of nodes, 6000 topology graphs have been generated. This was necessary in order to reduce the standard deviation from our results. For each topology, we calculate the average distance between the nodes, and set the communication range to that value. The most connected node is then selected, i.e., the node that has the greatest number of neighbors (highest neighbors density). The reasoning behind this is to choose a highly connected node instead of an isolated partition. Finally, for every simulation run, we vary the probability of unsuccessful message transmission from 15% to 60%, in order to observe the behavior of retransmission attempts and the reliable message delivery. We compare the results with the same conditions with a protocol that has a fixed threshold set to 20 retransmission attempts. For our purpose, this represents a high value of threshold.

As the selected topology and the network-wide connectivity can significantly influence the outcome of the simulation, we considered both random and grid realistic network topologies of size 100 × 100, by means of GenSeN [33], a tool validated for comparing real deployment strategies and experiences, with realistic wireless network topologies. More details can be seen in Table 1. For the comparison purpose, the results have been plotted with a slight offset, so that overlapping regions can be clearly identified.

The regular deployment can be depicted in Figure 2 (a). In this strategy it is important to create a network where each device is evenly separated from neighboring devices by a distance equal to the communication range. The random deployment seen in Figure 2 (b) illustrates a 3D strategy where the operator drops the devices from a higher point. Such a strategy intends to simulate a wireless sensor node experiment were the phenomenon is located far bellow the operator, or even to simulate the deployment from inside a helicopter. Figure 2 (b) reflects how the distribution follows a tendency of nodes to group together near the center of the deployment area.

Table III-A and III-B show respectively the simulation results for two network topologies considered.

A. Random Deployment

As expected, once a threshold is reached and message retransmission attempts are halted, reliability of the broadcasting

![Figure 1](image1.png)

Figure 1. Practical example. Discrete value (circles) and analytical trend (continuous lines) for ETA vs PLP in a 1 and 2 hop transmission.

![Figure 2](image2.png)

Figure 2. (a) Regular and (b) random deployment strategies, generated with GenSeN.
is reduced. We have plotted the results from the random deployment simulations in Figure 3 (a). While a mechanism such as flooding (i.e., with a high retransmission attempt threshold) delivers messages to 100% of the nodes on most of the runs, with a LQ-based threshold, reliability drops to as low as 68% when the link-quality is very low (i.e., 60% of message transmission failure). Figure 3 (b) shows the raw number of retransmission attempts for the same set of data. While our results have no explicit equation to map to the energy usage, we can clearly see that our link-quality estimator helps reduce the message retransmission drastically, while maintaining an adequate message delivery reliability.

In order to quantify our LQ estimator, we measure the effectiveness of each retransmission attempt for the packets that are effectively transmitted and acknowledged by a 2-hop neighbor, i.e., the ratio between the number of received packets and the attempts to deliver those packets. Figure 3 (c) compares the effectiveness of retransmission attempts in our ETA approach (i.e., with LQ threshold), with those obtained in a traditional technique (i.e., with high retransmission attempt threshold). With LQ-based threshold, every retransmission counts, since whenever there are more attempts than expected, the packet is simply dropped. While this decreases the reliability, it increases the energy efficiency.

B. Regular Deployment

Regular deployment is done following an evenly spaced grid with mobile devices. To ensure an expressive network coverage, we increased the number of nodes used in this type of deployment. While the difference between the high threshold and the LQ-based threshold exists (as can be seen in Figure 4 (a)), the difference is not as large as seen in the random deployment.

We can observe that when a failure is added into the simulation, the network becomes partitioned into many disconnected clusters, and the network coverage is reduced. We validated this through additional simulation runs. In a regular deployment, the LQ-based estimator is still capable of identifying when to limit the retransmission attempts. In fact, in this type of deployment, LQ-based estimator provides comparable reliability, with fewer transmission attempts.

As seen in Figure 4 (c), effectiveness is actually better than in random deployment, but the same behavior is noted.

IV. Conclusions

Energy efficient wireless networks is an inevitable trend for the operators, equipment manufacturers, as well as other related industries. In this paper, we aim to define an estimator
that is capable of not only dealing with omission faults, but to allow for scalability as well. We propose a link-quality estimator that combines different approaches to reliability in a way that allows devices to selectively transmit a message while achieving a high message delivery ratio and lowering the energy usage.

Our estimator establishes a dynamic threshold on the number of transmission attempts for a certain message, therefore eliminating unnecessary retransmission attempts. At the same time, this threshold will help enforce at least a minimum number of transmissions, therefore ensuring better message delivery. As a proof-of-the-concept, our study is based on the network-wide broadcasting. Simulations results are obtained for a random, as well as a regular deployment. Our proposed link-quality estimator show adequate reliability and message delivery, while using minimal amount of message retransmissions.

Further progress in the energy efficient networks will certainly be very helpful in enhancing its usefulness. As a future work, we plan on investigating the performance of the proposed approach in a more realistic scenario with correlated packet losses.

REFERENCES