X-FDR: A Cross-Layer Routing Protocol for Multi-hop Full-Duplex Wireless Networks

M. Omar Al-Kadri, Adnan Aijaz, and Arumugam Nallanathan

***Abstract*—The recent developments in self-interference (SI) cancellation techniques have led to the practical realization of full-duplex (FD) radios that can perform simultaneous transmission and reception. FD technology is attractive for various legacy communications standards. In this paper, after discussing the opportunities of FD technology at the network layer, we present a cross-layer aided routing protocol, termed as X-FDR, for multi-hop FD wireless networks. X-FDR exploits a Physical (PHY) layer model capturing imperfection of SI cancellation. At the medium access control (MAC) layer, X-FDR adopts an optimized MAC protocol which implements a power control mechanism without creating the hidden terminal problem. X-FDR exploits the unique characteristics of FD technology at the network layer to construct energy-efficient and low end-to-end latency routes in the network. Performance evaluation demonstrates the effectiveness of X-FDR in achieving the gains of FD at higher layers of the protocol stack.**

***Index Terms*—full-duplex, cross-layer, distributed networks, routing, energy-efficiency, MAC.**

I. Introduction

Recent advances in self-interference (SI) cancellation techniques have made in-band full-duplex (FD) [1], [2] operation feasible for wireless communications. FD-capable nodes can perform simultaneous transmission and reception on same resources in time and frequency domains. FD technology not only offers the potential of (theoretically) doubling the capacity and the spectrum utilization but also assists in solving some of the key problems in half-duplex (HD) networks, such as the hidden node issues, loss of throughput due to high congestion rates, and large end-to-end delays [1]. Existing efforts towards FD communications have mainly investigated Physical (PHY) layer aspects; however, solutions for medium access control (MAC) and highers layers have also started to emerge [3]. In order to reap the maximum benefits of FD technology, optimizations are required at different layers of the protocol stack.

On the other hand, energy saving in distributed wireless networks is of significant importance due to the limited battery supply of each node. Nodes in the network continuously participate in route construction, and act as relays for neighboring nodes. In addition to continuous variation in channel conditions, this leads to a large amount of control messages being exchanged across the network, which potentially entails high energy consumption. Therefore, energy-efficiency in distributed wireless networks is an important issue. Moreover, with the introduction of FD, the issue of energy efficiency becomes critical owing to additional hardware and processing capabilities of nodes.

Research on routing protocols for FD wireless networks is still in infancy. In [4], Fang *et al.* have proposed cross-layer optimization for opportunistic multi-path routing in FD wireless networks. The route selection problem has been solved under various resource competitions and node constraints. However, the proposed framework assumes perfect SI cancellation. Kato and Bandai [5] have proposed an on-demand detour routing protocol for directional FD wireless networks. Although the use of directional antennas mitigates the hidden terminal problem, the protocol is not compatible with networks employing omnidirectional antennas. Sugiyama *et al.* [6] designed a directional asynchronous FD-MAC protocol for mitigating collisions in multi-hop FD wireless networks, however the protocol is not applicable to the omni-directional antennas, which are widely used in handheld devices. Ramirez and Aazhang [7] addressed the problem of joint power allocation and routing in FD wireless networks through a modification to Dijkstra's algorithm. However, the paper assumes that an FD MAC is in place. Besides, the main focus of the paper is system-level analysis. It is also important to mention that most of the existing studies do not fully exploit the key opportunities provided by FD technology, which have been discussed later. On the other hand, power-aware routing protocols [8] for conventional HD wireless networks have received significant attention over the last few years. It can be easily inferred that design of routing protocols for FD wireless networks requires further investigation from various aspects, which motivates this work.

Our objective in this paper is to design a cross-layer aided routing protocol for imperfect FD wireless networks, where the notion of imperfection implies that SI is not fully cancelled at the PHY layer. The proposed protocol, which is termed as X-FDR, is particularly designed for minimizing energy consumption and end-to-end latency in FD wireless networks. The key features of X-FDR can be summarized as follows. First, X-FDR accounts for residual self-interference (RSI) at the PHY layer. Second, X-FDR adopts an optimized (not necessarily optimal) MAC protocol that implements a power control mechanism without creating the hidden terminal problem. Third, X-FDR adopts a novel energy cost metric and exploits the opportunities provided by the FD technology e.g., the ability to sense the medium while transmitting. This provides immediate reaction to channel errors, and conse-

M. Al-Kadri is with the School of Computing Science and Digital Media, Robert Gordon University, Aberdeen, UK.

A. Aijaz is with the Telecommunications Research Laboratory, Toshiba Research Europe Ltd., Bristol, UK.

A. Nallanathan is with School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK.

Contact e-mail: o.alkadri@rgu.ac.uk

quently, nodes are able to send a burst of packets, constrained by the minimum buffer size (β_{min}) on the selected route. Moreover, nodes wait for the acknowledgement (ACK) of the last received packet only instead of acknowledging from the reception of each individual packet. Fourth, nodes in X-FDR employ immediate forwarding, which is enabled by their FD capabilities. A node does not have to wait for the reception of the full packet before it can forward it to the next hop. This feature reduces the end-to-end latency of the network. Last, but not the least, X-FDR employs a novel route maintenance process that reduces the latency due to new route discovery. Performance evaluation demonstrates that X-FDR provides a viable solution for multi-hop FD wireless networks.

II. Opportunities of FD at Network Layer

In this section, we describe the key opportunities provided by the FD technology that could potentially be exploited by network layer protocols.

- **Immediate Forwarding** – FD technology enables simultaneous transmission and reception, which is particularly attractive in multi-hop wireless networks. When a FD node starts receiving a packet, it can simultaneously start forwarding it to the next hop. This provides a paradigm shift from conventional *store-and-forward* architecture in legacy HD networks, to *receive-and-forward* architecture. For example, consider the scenario depicted in Fig. 1. With immediate forwarding, node A can start transmitting the packet, which is being received from node S, to next hop, as soon as it has processed the packet header. Immediate forwarding is particularly attractive to reduce end-to-end latency and improve throughput in multi-hop wireless networks.
- **Continuous Sensing** – Another key advantage of FD technology is the ability to sense the medium while transmitting. In conventional HD networks, a node will not be notified of transmission errors, until after the transmission is complete. With continuous sensing, FD nodes can detect an erroneous transmission as soon as it occurs, which leads to immediate termination of a transmission. This improves resource utilization and potentially enables reduction of end-to-end latency.
- **Burst Transmission** – The continuous sensing property further enables FD nodes to send burst of data packets, such that only the last packet is acknowledged. This is unlike conventional HD networks where packets are sent sequentially and each packet needs to be individually acknowledged. If properly exploited at the network layer, this feature has the potential to not only reduce end-to-end latency, but also improve resource utilization (particularly for signaling resources) and throughput.
- **Faster Convergence** – The above mentioned features, especially immediate forwarding, enable faster dissemination of signaling information associated with routing protocols. Hence, faster topological convergence can be achieved, especially for those routing protocols that rely on building a topology tree of the network. Besides, these features can also enhance the efficiency of flooding-based routing protocols.
- **Secure Routing** – Having two simultaneous transmissions on the same frequency makes it difficult for a nearby node to perform eavesdropping attacks as the received signal would be a scrambled mix of both signals. Hence, such attacks on intermediate nodes become significantly more complex to perform, thereby enhancing the security of the routing protocol between source and destination nodes.

It is emphasized that some of the key opportunities like immediate forwarding, continuous sensing, and burst transmission have been exploited in the design of X-FDR. These opportunities have been further explained while discussing the protocol operation.

III. Network Model

We consider a distributed network comprising N FD wireless nodes indexed by the set $\mathcal{N}$. Let, $\mathcal{R}$ denote the set of all possible routes in the network. A route $R \in \mathcal{R}$ represents an ordered set of nodes between a source node S and a destination node D. For example, Fig. 1 demonstrates a route comprising four nodes in the network.

We assume that FD wireless nodes employ necessary SI cancellation techniques at the PHY layer. Since SI cancellation techniques are not perfect in practice, a node experiences RSI. We use an experimentally characterized model [9] for RSI, based on which, the power of the RSI signal is given by $\frac{P_t^{(1-\rho)}}{\Delta \cdot \chi^{\rho}}$, where P_t is the transmit power, Δ is the interference suppression factor, χ depends on the SI cancellation technique, and ρ denotes the SI cancellation capability. Note that $\rho = \infty$ denotes perfect SI cancellation, resulting in zero RSI. Moreover, $\rho = 0$ implies a constant reduction in transmission power. Realistically, $0 < |\rho| < 1$; with $\rho = 1$ implying a constant power, for RSI similar to noise.

We assume that the received signal power at a node j, based on a transmission from a node i at maximum transmit power P_{max} is given by $P_r = P_{max} \cdot |h_{i,j}|^2 \cdot d_{i,j}^{-\alpha}$, such that $h_{i,j}$ is the channel coefficient that accounts for small-scale fading, $d_{i,j}$ denotes the distance, and α denotes the path loss exponent. We assume that nodes in the network employ a power control mechanism based on the received signal strength such that the controlled power level is determined by $P_{ctrl} = P_{max} \cdot (P_r)^{-1} \cdot \zeta^{th} \cdot \hat{c}$, such that ζ^{th} denotes the minimum required received signal strength and $\hat{c}$ is a constant [10]. Please note that RSI is not part of P_{ctrl} as FD communication is not yet initialized. The impact of RSI and cumulative interference is captured on link-level. Further, our link-level model is based on signal-to-interference-plus-noise-ratio (SINR) which accounts for RSI and given by

$$SINR = \frac{P_i |h_{i,j}|^2 {d_{i,j}}^{-\alpha}}{RSI + I_x + N_0},$$

where P_i denotes the transmit power of node i (either P_{max} or P_{ctrl}) and N_0 denotes the noise power. Moreover, I_x is the cumulative interference from neighboring nodes and is given by $I_x = \sum_{x \in \mathcal{N} \setminus \{i,j\}} P_x |h_{x,i}|^2 {d_{x,i}}^{-\alpha}$, where P_x is the transmitting power of an interfering node x, $h_{x,i}$ is the channel

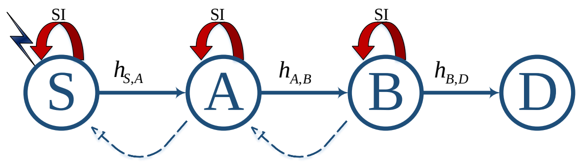

Fig. 1: Example of a route $R = \{S, A, B, D\}$. Straight lines represent the intended transmission, while dotted lines represent neighbouring interference, and the red semi-circled arrows represent SI.

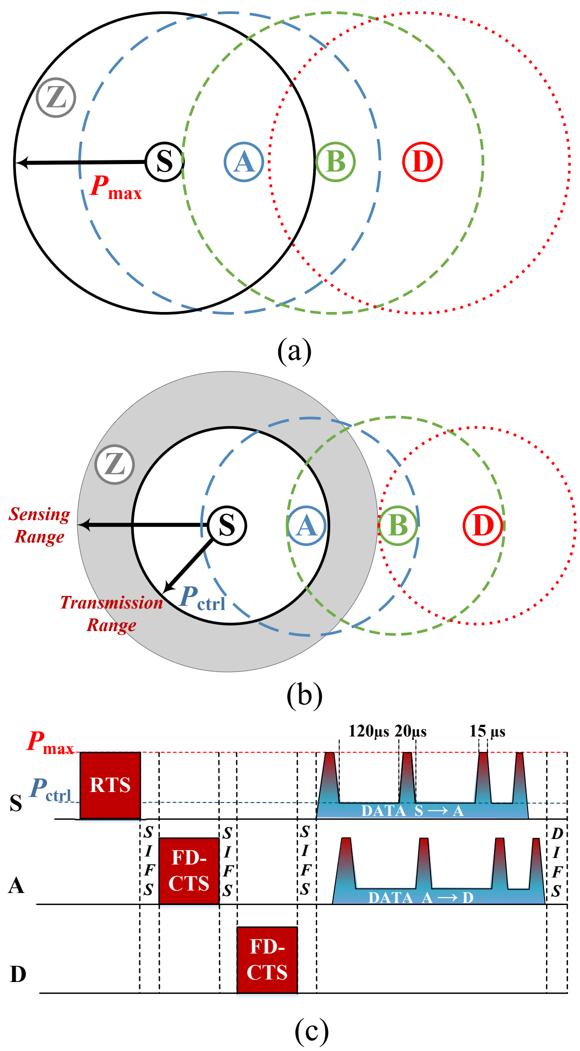

Fig. 2: (a) Ranges of nodes transmitting control signals using P_{max}; (b) ranges of nodes after application of power control; (c) illustration of a uni-directional FD transmission at the MAC layer.

coefficient between nodes x and i, and $d_{x,i}$ is the distance between nodes x and i.

IV. MAC Layer Design for X-FDR

This section presents the MAC layer design for X-FDR. In X-FDR, we adopt the modified version of our recently proposed MAC protocol [11] for distributed wireless networks. The MAC protocol in [11] enables both bi-directional FD transmissions and uni-directional FD transmissions. The former enables simultaneous two-way transfer of two distinct data streams between a pair of nodes, whereas, the latter involves three nodes and same data stream is forwarded from one node to another via an intermediate relay node. In X-FDR, we focus only on uni-directional FD transmission. We also omit the MAC layer ACK procedure.

We explain the protocol operation with the aid of Fig. 2. Let $N = \{S, A, B, D\}$ be a set of nodes involved in the intended transmission, where S is the source node and D is the destination node. After sensing the spectrum idle, node S starts the transmission by sending a request-to-send (RTS) packet to node A using P_{max}. After receiving the RTS packet from S, node A waits for short inter-frame space (SIFS) duration before sending an FD clear-to-send (FD-CTS) packet [11] to both S and B. The FD-CTS packet includes the source and next hop addresses along with the transmission duration. Note that FD-CTS is also transmitted using P_{max} to capture the channel for forwarding. Using the received RTS from S, node A calculates P_{ctrl} as described in Section III. Node S calculates its P_{ctrl} as well using the FD-CTS received from node A. Further, when node B receives the FD-CTS from node A, it replies with FD-CTS as well, and calculates its P_{ctrl} based on the received power from A. After that, node A recalculates P_{ctrl} based on the received FD-CTS from B and compares it with the previously calculated P_{ctrl}, where the higher P_{ctrl} is chosen to maintain connection with both S and B. Similarly, the rest of the relaying nodes attempt to acquire the channel until the intended destination is reached.

During data transmission, nodes use P_{ctrl} with periodical increase to P_{max}, so that nodes in the carrier sensing zone, which cannot successfully decode the transmission and set their Network Allocation Vector (NAV) to Extended Inter-Frame Space (EIFS) duration can sense the transmission. Note that the period between two successive power increase intervals must be less than the EIFS duration[1]. These periodic increments preserve the channel, and ensure that nodes in the carrier sensing zone will not attempt to initiate a transmission.

A. Hidden Terminal Problem

Referring to Fig. 2b, consider that nodes S and A constitute a sender-receiver pair in HD mode. Node Z, which resides in the carrier sensing range of S but not of node A, may act as a hidden node. In FD transmission, hidden nodes may affect the reception of control signals at node S. Therefore, in the proposed protocol we adopt RTS-CTS handshake mechanism. Moreover, by sending FD-CTS using P_{max}, the protocol ensures that nodes in the carrier sensing ranges are aware of an ongoing transmission. After power control is applied for data transmission, node Z can again create a hidden node problem, which is why the periodic increments from P_{ctrl} to P_{max} are required.

[1] According to the IEEE 802.11n standard [12], 15 μs is suitable for carrier sensing, and 2 μs is adequate to increase/decrease the power level from/to 10% to/from 90%. Therefore, a duration of 20 μs is deemed adequate for transition of power level from P_{ctrl} to P_{max} and vice versa. Since EIFS is set to 120 μs, nodes will transmit at P_{max} every 120 μs for a duration of 20 μs, and the cumulative transmission duration is less than the EIFS duration.

V. X-FDR: Protocol Operation

This section explains the protocol operation of X-FDR. Unlike conventional Adhoc On-demand Distance Vector (AODV) routing protocol [13], where the route cost relies mainly on hop count, X-FDR uses energy consumption as the key metric for route cost estimation.

A. Route Cost Estimation

Since X-FDR is a cross-layer routing protocol, all relevant factors must be accounted for in route cost estimation. Nodes in the network initiate connections using RTS/FD-CTS messages with maximum power level P_{max}, in order to restrain other nodes residing in the sensing range from initiating an interfering transmission. Once the data transmission take place using controlled power level P_{ctrl}, a periodic increase of power to P_{max} takes place to stop potential interference and eliminate the problem of hidden nodes; therefore, the metric for route cost shall account for different power levels.

In a route $N = \{S, A, B, D\}$, the cost of energy for sending data from node S to node A can be estimated as $\rho_{(S,A)} = \chi(E_{data}+E_{ctrl}+E_{on})$, where $\chi = 1/\mathcal{P}_f$ is the the number of retransmissions attempts such that $\mathcal{P}_f$ denotes the probability of transmission failure, and E_{data}, E_{ctrl} and E_{on} denote the energy consumed during data transmission, control signal transmission and when the receiver is turned on, respectively. The energy consumption during data transmission phase can be calculated as $E_{data} = P^S_{ctrl}(\beta_{min}/r - T_{inc}) + P_{max}T_{inc}$, where P^S_{ctrl} and P_{max} denote the controlled power level and maximum transmit power of node S, respectively, β_{min} is the minimum buffer size (explained in Section V-B), and r is the data rate. Moreover, T_{inc} denotes the duration of the periodic increase/decrease in power levels. The energy consumption during control signal transmission can be calculated as $E_{ctrl} = P_{max}(T_{RTS}+T_{FD-CTS})$, where T_{RTS} and T_{FD-CTS} denote the duration of RTS and FD-CTS messages, respectively.

Assume that there exists a route $R_i = n_o \rightarrow n_1 \rightarrow ... \rightarrow n_k$ from the source node S to the destination D, where, without loss of generality, $S = n_0$ and $D = n_k$. Therefore, the total cost, $\bar{\rho_i}$, along the route $\mathcal{R}_i$ can be expressed as

$$\bar{\rho_i} = \sum_{j=0}^{k-1} \rho_{(j,j+1)}(P_j),$$

where P_j is the power level used by node n_j to communicate with node n_{j+l}, and $\rho_{(j,j+1)}(P_j)$ is the relaying cost between nodes n_j and n_{j+l}. Assuming that there are x routes from source to destination, the objective of the routing protocol is to select the route with minimum energy consumption i.e., $R_{min} = \arg\min(\bar{\rho_i}), \quad \forall\ i = 1, 2, \ldots, x$.

B. Route Discovery

The first stage of X-FDR is route discovery. When a source node S requires a route to destination node D, it broadcasts a Route REQuest message (RREQ). Once neighbouring nodes receive RREQ, they calculate the energy cost, ρ, add it to RREQ and broadcast it to the neighboring nodes. After that the neighboring nodes calculate the new ρ, add it to the previous

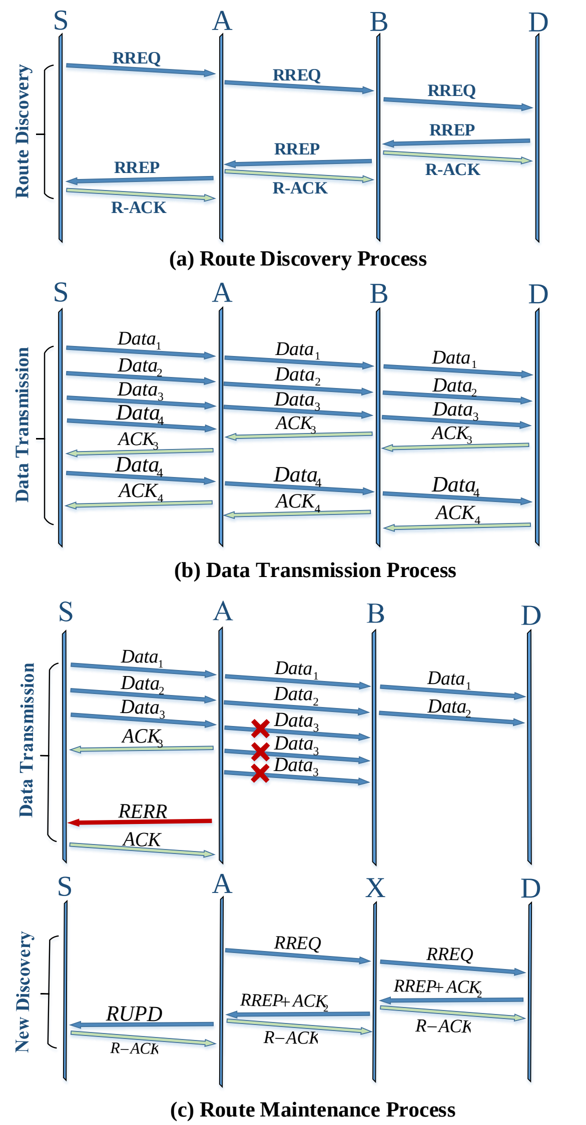

Fig. 3: Example of (a): route discovery process; (b) data transmission process; (c) route maintenance process in X-FDR.

cost received in RREQ, and broadcast it further until it reaches the destination D. The destination node sets up a timer to allow several RREQ messages to arrive from different routes. After the timer expires, node D chooses the route R_{min} with minimum energy consumption and replies with a Route REPly (RREP) message via R_{min}. The routing table of each node is refreshed, whenever it receives RREQ/RREP messages. Each node maintains a received RREQ table and compares the new RREQ messages in order to eliminate the duplicate RREQ messages. Additionally, a Route-ACKnowledgement (R-ACK) packet is used by the nodes receiving RREP, in order to confirm successful reception of the RREP packet and establishment of the route. Fig. 3 demonstrates an example of route discovery performed by node S, where R_{min} is found to be $\{S, A, B, D\}$.

Instead of sending packets sequentially and waiting for acknowledgements (ACKs) for each data packet, X-FDR sends a burst of packets, such that the number of packets in each burst is determined by the minimum buffer size, β_{min}, of the nodes in the route R. For example, let β_S denote the buffer size (in terms of the number of packets) of node S. Further, node S encapsulates $\beta_{min} = \beta_S$ within RREQ and broadcasts it. When a neighboring node A receives RREQ, it compares β_{min} with its own buffer size (i.e., β_A). If $\beta_A < \beta_{min}$, node A updates $\beta_{min} = \beta_A$ in RREQ and broadcasts it forward. However, if $\beta_A > \beta_{min}$, node A keeps the buffer size as it is and forwards RREQ. When D receives RREQ, it compares its buffer size with the received β_{min}, and sends the lowest of the two within RREP, which informs node S with the minimum buffer size to be used for data transmission. Note that if a node in the route does not have a buffer enabled, β_{min} will be set to 1.

C. Data Transmission

When node S receives the RREP message as a result of route discovery process, it becomes aware of the most energy-efficient route to the destination D. After the route discovery process, node S starts transmitting a burst of data packets to next hop (node A), where the number of packet in each burst is given by β_{min} of the route. In conventional HD communications, when node S sends a burst of data, it will not be notified of transmission errors, e.g., by receiving a Route ERRor (RERR) message, until after the entire burst is transmitted. This incurs significant waste of time and resources. However, using continuous sensing offered by FD technology, node S can sense a problem in the transmission as soon as it occurs, which leads to immediate termination of the transmission. Hence, node S continuously senses the packets forwarded by node A and stops transmitting immediately if it receives RERR message.

Since node A is FD-capable, it can employ *immediate forwarding*, wherein it does not have to wait for the entire packet to be received before forwarding. Once node A receives all the packets, determined by β_{min}, it replies with an ACK to acknowledge the reception of the last packet. If a packet is dropped while the route is not deemed faulty, node S gets notified by the ACK packet sent by A, and it retransmits the lost packet. The same process is repeated at each hop until the destination is reached. Note that each node in the route only notifies the previous hop with an ACK. This is because data is assumed to be buffered by the previous node in the route as β_{min} is known to all nodes. Therefore, if a node did not receive all the packets, it would request these from previous nodes using ACK.

For instance, assume that $\beta_{min} = 4$, and consider the scenario demonstrated in Fig. 3. Node S transmits data packets 1 through 4 while continuously sensing the signal transmitted by A. Node A starts forwarding immediately; however it only receives 3 packets. Therefore, it sends an ACK for data packet 3, which notifies S that it needs to retransmit data packet 4. Note that if the buffer size of node S is larger than the amount of data packets that needs to be sent, it will include an end-of-queue (EQ) notification message with the last packet, in order to avoid an unnecessary retransmission.

D. Route Maintenance

The process of route maintenance is depicted in Fig. 3, where the transmission of packets 1 to 3 from source S to destination D is exemplified. First, node S transmits the burst of packets to node A. Node A receives the packets successfully and responds with an ACK packet to the source S to confirm the successful reception. As node A receives the packets, it starts forwarding them to node B. However, node B fails to receive the data packet 3 successfully, despite maximum number of retransmission attempts by node A due to a link error. Once the pre-set timer expires at node A without receiving any ACK from node B, it infers that the link $A{-}B$ is broken and sends an RERR message to its previous hop, which is node S in this case. The RERR message informs node S of a link failure and a new route discovery process. Node S updates its routing table and marks link $A-B$ as broken, and then acknowledges the RERR of node A. Since the route error occurred at node A, it initiates a new route discovery process by broadcasting a RREQ message. Intermediate nodes follow the same procedure as described earlier for route discovery. When the destination node D receives RREQ from node A, prior to the full reception of packets in the same burst of β_{min}, it knows that the request is to complete the same data stream, and replies with RREP, piggybacked with an ACK packet to inform node A about the last packet node D had received. After receiving the RREP message, node A sends a Route UPDate (RUPD) message, with the new β_{min}, to the previous hop i.e., node S, to inform it of a new route. Finally, node A starts new data transmission to destination D from data packet 3 onwards. If node S has new burst of data to send, it will use the updated route towards node D, starting the transmission after sensing the last packet sent by node A. The process of route maintenance is summarized in Algorithm 1. ■

Remark 1 – It is worth emphasizing that X-FDR incurs less overhead and complexity as compared to its HD counterparts. First, it omits the MAC layer ACK procedure which reduces the signaling overhead. Second, from the routing perspective, the overhead in most cases is reduced which simplifies the system design. For instance, in the route discovery process, ACK packets are only sent to acknowledge the RREP packets which reduces the overhead significantly as compared to acknowledging the RERR packets. Similarly, acknowledging a burst of packets instead of each packet reduces the overhead in the network.

Remark 2 – Some recent studies [14], [15] have investigated the problem of *in-band wireless cut-through* which is closely related to the problem of multi-hop transmissions in FD wireless networks. To realize wireless cut-through transmissions, specialized hardware is required for cancellation of all types of interference. It is worth emphasizing that the need for MAC and routing protocols cannot be eliminated for realizing wireless cut-through transmissions. X-FDR adopts a cross-layer approach for multi-hop transmissions in FD wireless networks and focuses only on SI cancellation which can be achieved through state-of-the-art FD radios. X-FDR can directly benefit from additional hardware capabilities as realized for wireless cut-through transmissions. Alternatively, the cross-layer approach of X-FDR can improve the efficiency of wireless cut-through solutions.

Algorithm 1: Route Maintenance Process in X-FDR

```
Input: Source: S, Destination: D, Nodes: N, R_min
Output: New Route: Updated R_min
while S → D do
    Nodes forward incoming packets
    for each node i ∈ {R_min \ D} do
        i transmits packets to i + 1
        i sets timer t_ACK
        if i receives ACK_z while t_ACK≠0 then
        i forwards packets z + 1
        else i marks link i → (i + 1) as broken
        Send RERR to node i − 1
        Nodes i − (x + 1), x ∈ {0, 1, ···, hops to S}
          traverse RERR back to S
        i broadcasts RREQ
        if D receives RREQ for the same stream then
            set a timer t_max
            if t ≤ t_max then
            continue receiving RREQ packets
            else stop receiving RREQ packets;
            compare received RREQ packets and select
              R_min
            return RREP packet with R_min and β_min.
            if i receives new RREP then
                Update R_min
                Send RUPD to node i − 1
                Nodes i − (x + 1),
                  x ∈ {0, 1, ···, hops to S} update R_min
                  and send RUPD back to S
                Closest node to D with full β_min
                  received will resume transmission
            end
        end
    end
end
```

VI. Performance Evaluation

In this section, we conduct a performance evaluation of X-FDR. We have implemented X-FDR in OPNET. Necessary changes were made in the node and protocol models to implement simultaneous transmission and reception. We assume that nodes are randomly distributed in an area of 500 m^2. The buffer size is assumed to be fixed and set to 10 kB. The maximum transmit power of a node is set to 23 dBm (200 mW). We assume a channel bandwidth of 2 MHz. The path loss exponent is set to 4. We consider file transfer protocol (FTP) application with packet size of 1 kB. The RSI parameter, χ is set to 13 dB. The simulation results are averaged over 10 iterations. In each iteration, source and destination nodes are randomly selected. We have modified the wireless model in OPNET to account for RSI and Rayleigh fading. For performance comparison, we select two different baseline protocols: AODV and FD version of AODV, termed as FD-AODV, wherein nodes employ immediate forwarding and acknowledge each packet. Moreover, both AODV and FD-AODV do not employ power control.

Fig. 4a shows the average power consumption of routes from source to destination nodes selected by different protocols. First, we note that the power consumption increases with the number of nodes in the network. This is due to inclusion of more nodes in the routes selected by different protocols. Second, we note that X-FDR outperforms both baseline protocols by performing up to 40% and 50% better than AODV and FD-AODV protocols, respectively. The performance gain of X-FDR in terms of energy-efficiency is primarily due to the use of power control at the MAC layer, which limits the effect of interference, and the adoption of energy-based routing cost metric. Third, we note that SI cancellation plays an important role in power consumption. A higher SI cancellation capability, corresponding to higher values of Δ and ρ, reduces the power consumption due to less number of transmission failures due to interference.

Fig. 4b shows network throughput against the number of network nodes. We note that X-FDR outperforms AODV by performing up to 50.2% and 21.2% better under high and low SI cancellation scenarios, respectively. This is primarily due to the FD features of X-FDR. Further, X-FDR achieves nearly 8.6% lower throughput than FD-AODV under high SI cancellation scenario. This can be attributed to the employment of power control in X-FDR as there is an inherent trade-off between power and throughput. Note that the presence of SI, due to low SI cancellation capability, can degrade the performance of FD-AODV to the extent that it achieves lower throughput than AODV. Such performance degradation is also visible in case of X-FDR.

Fig. 4c plots the average hop count between randomly located source and destination nodes, as a function of number of nodes in the network. The average hop count increases with the number of network nodes as more nodes are involved in the selected routes.We note that X-FDR has higher average hop count than the baseline protocols. This is because both AODV and FD-AODV use hop count as the routing metric. However, X-FDR focuses on routes with minimal energy consumption, and therefore, it incurs higher hop count with lower total energy consumption.

Fig. 4d plots the average end-to-end delay against the number of network nodes. We note that X-FDR outperforms AODV by achieving up to 33% lower delay, due to the use of immediate forwarding, continuous sensing and burst transmission mode. On the other hand, FD-AODV outperforms X-FDR by achieving up to 12% lower delay. This is due to the fact that X-FDR incurs higher hop count. Although both AODV and FD-AODV incur similar hop count, the latter achieves lower delay due to immediate forwarding feature. It is important to mention here that the results in Fig. 4d correspond to the scenario when the route does not suffer any failures along its path. In order to capture the impact of route maintenance, we deliberately mark nodes to fail (an option provided by OPNET) across the route during transmission process and evaluate end-to-end delay in Fig. 4e. Initially,

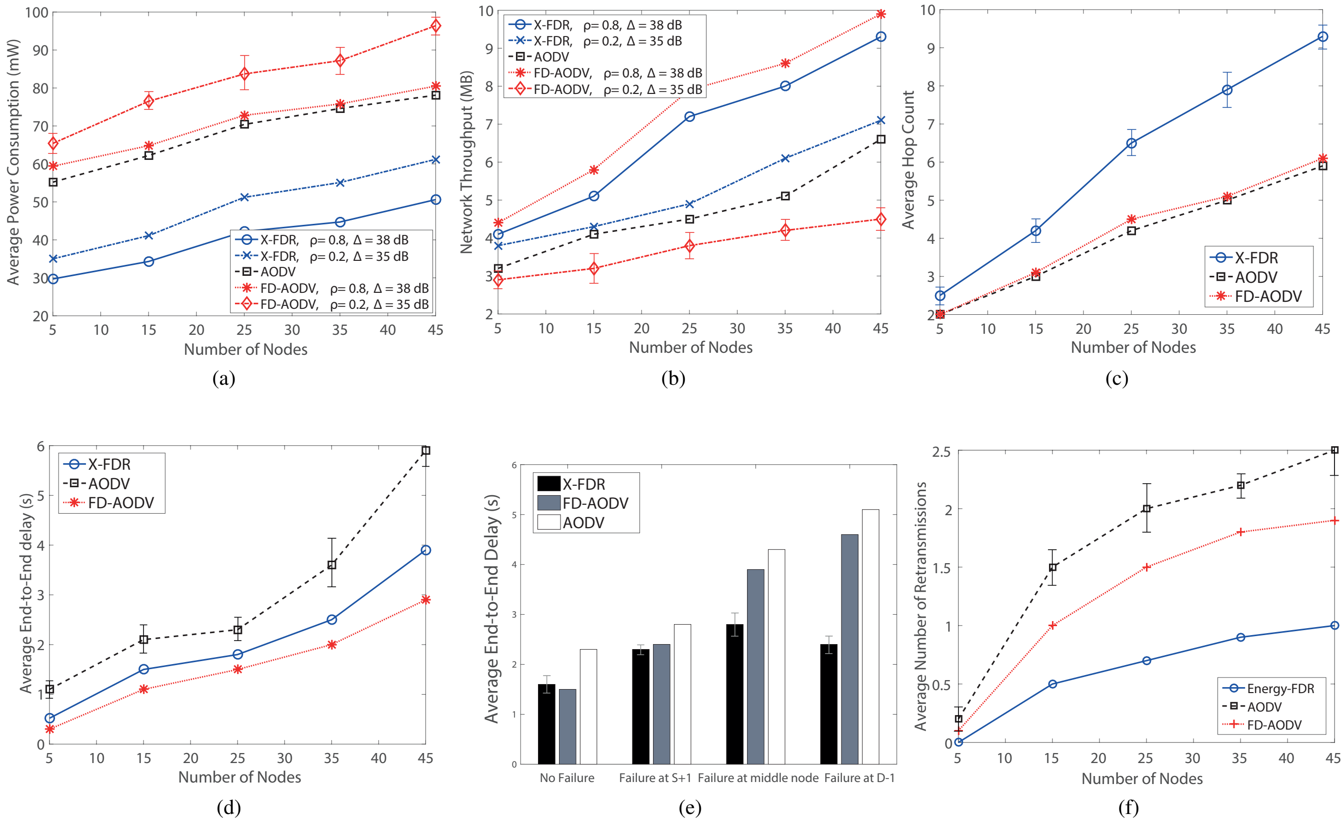

Fig. 4: Performance evaluation of X-FDR: (a) average power consumption; (b) network throughput; (c) average hop count; (d) average end-to-end delay; (e) average end-to-end delay with node failures (number of network nodes = 25); (f) average MAC layer retransmissions. The confidence intervals on different figures are also shown.

we fail the first node after the source, then a node at the middle of the route, and finally, a node right before the destination for worst case scenario. As shown by the results, X-FDR outperforms both AODV and FD-AODV by performing up to 39% and 34% better than the former and the latter, respectively. The performance gain is due to the proposed route maintenance procedure that initiates a route discovery process at the last buffered node instead of starting new route discovery process by the source.

Fig. 4f shows the average number of MAC layer retransmission attempts against the number of network nodes. The average number of retransmissions increase with the number of network nodes due to higher probability of failures as a result of higher inter-node interference. We note that X-FDR incurs the lowest number of retransmissions than both AODV and FD-AODV. This is primarily due to an optimized MAC protocol that minimizes collisions due to hidden node problem while using power control.

Finally, a qualitative comparison of X-FDR against state-of-the-art protocols is given in TABLE I.

VII. Concluding Remarks

FD technology has the potential to play an important role in realizing the capacity objectives of future wireless networks. Realizing the FD capability at higher layers of the protocol stack is particularly attractive to reap the full potential of FD technology. In this paper, we have designed a cross-layer routing protocol, termed as X-FDR, for multi-hop FD wireless networks with imperfect SI cancellation. X-FDR accounts for RSI at the PHY layer, adopts an optimized MAC protocol with power control feature, and exploits the opportunities provided by FD technology at the network layer. Performance evaluation demonstrates that X-FDR outperforms baseline protocols in terms of power consumption without a significant compromise on network throughput. Besides, it achieves lower end-to-end delay in the presence of route failures. Hence, X-FDR provides a viable solution for multi-hop FD wireless networks.

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TABLE I: Qualitative Comparison of Different Routing Protocols for FD Wireless Networks

Feature/Protocol	**OMR** [4]	**D-FDW** [5]	**M-DA** [7]	**AODV**	**FD-AODV**	**X-FDR**
Residual SI	No	No	Yes	No	Yes	Yes
Power Control	No	No	No	No	No	Yes
Directional Antennas	No	Yes	No	No	No	No
Optimized MAC	Yes	Yes	No	No	No	Yes
Immediate Forwarding	No	Yes	No	No	Yes	Yes
Continuous Sensing	No	No	No	No	No	Yes
Burst Transmission	No	No	No	No	No	Yes
Energy Efficiency	No	No	No	No	No	Yes

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M. Omar Al-Kadri (M'17) received the B.Eng. degree in Computer Engineering from IUST, Syria, in 2010, the M.Sc. degree (with distinctoin) in Networking and Data communication from Kingston University, UK, in 2013, and the Ph.D degree in Telecommunication engineering from King's College London, UK, in 2017. He is now a lecturer in networking and cyber security at Robert Gordon University, UK. His current research interests include security of wireless communications with application to healthcare, full-duplex communications, HetNets, and MAC/routing protocols.

Adnan Aijaz (M'14–SM'18) received his Ph.D degree in Telecommunications Engineering from King's College London (KCL), UK, in 2014. After a post-doctoral year at KCL, he moved to Toshiba Research Europe Ltd. where he is currently a Senior Research Engineer. His recent research interests include 802.11-based WLANs, 5G cellular networks, Industrial IoT, Tactile Internet, and full-duplex communications. His publications have been featured in internationally renowned conferences and journals.

Prior to joining KCL, he worked in cellular industry for nearly 2.5 years in the areas of network performance management, optimization, and quality assurance. He holds a B.E. degree in Electrical (telecom) Engineering from National University of Sciences and Technology (NUST), Pakistan.

Arumugam Nallanathan (M'00–SM'05–F'17) is Professor of Wireless Communications and Head of the Communication Systems Research group in the School of Electronic Engineering and Computer Science at Queen Mary University of London since September 2017. Previously, he held academic positions with the Department of Informatics at King's College London, UK and the Department of Electrical and Computer Engineering, National University of Singapore. His research interests include 5G Wireless Networks, Internet of Things and Molecular Communications. He is a co-recipient of the Best Paper Awards presented at the IEEE International Conference on Communications 2016 and the IEEE Global Communications Conference 2017. He is an IEEE Distinguished Lecturer. He has been selected as a Web of Science Highly Cited Researcher in 2016.

He has been an editor for various IEEE journals and served as the chair and member of numerous IEEE conferences. He received the IEEE Communications Society SPCE outstanding service award 2012 and IEEE Communications Society RCC outstanding service award 2014.