White Paper

# BATS Protocol:

## A Unified Integrated-Access-and-Backhaul Solution based on Network Coding

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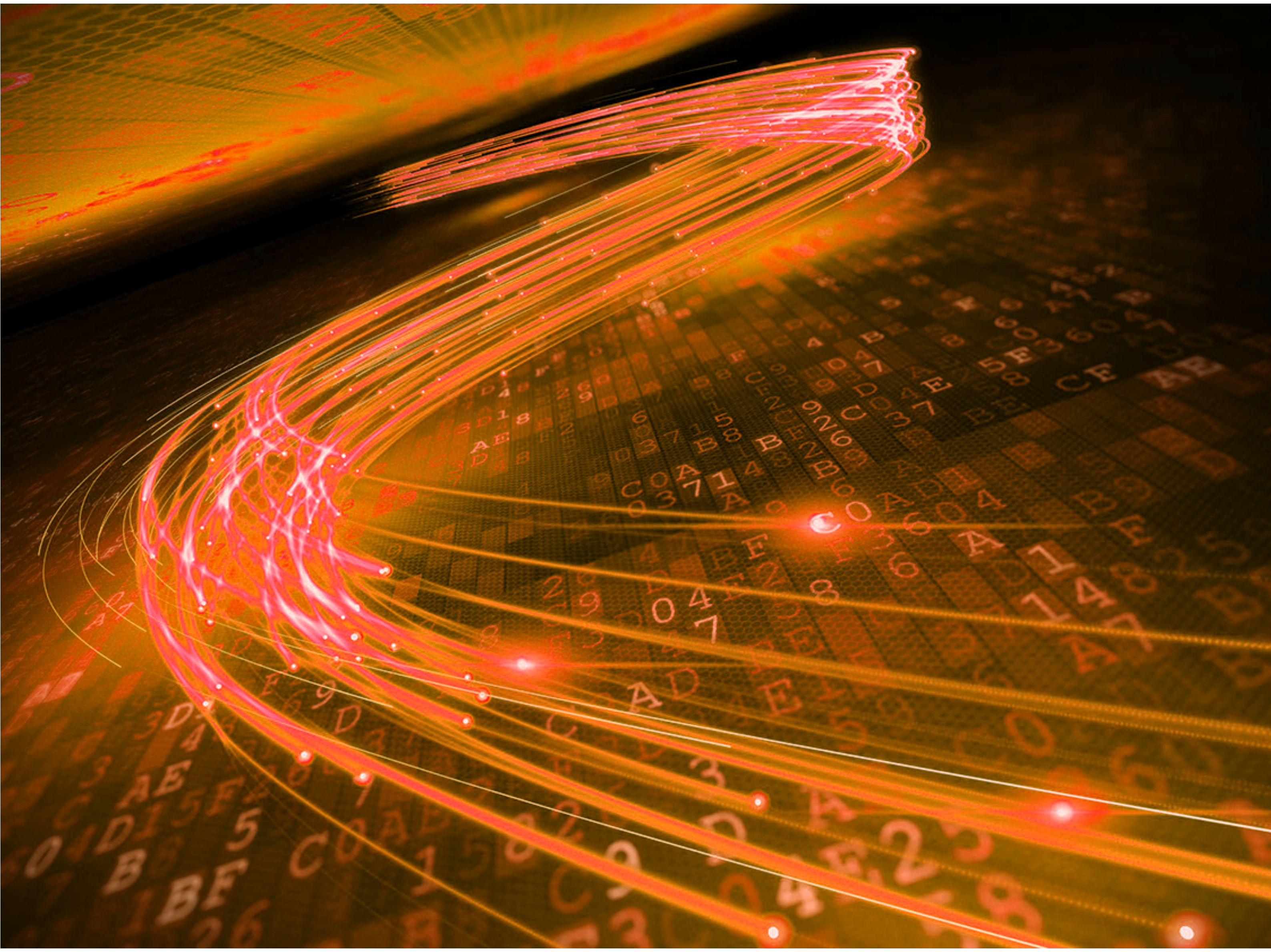


## About the Authors

The authors are the inventors of BATS, a disruptive network coding technology that makes wireless multi-hop communication a reality. Network coding is a cross-disciplinary field of research co-founded by Raymond Yeung at the turn of the last century that has induced a paradigm shift in network communications. Shenghao Yang and Raymond Yeung are faculty members at The Chinese University of Hong Kong. They are also co-founders of n-hop technologies that pioneers the applications of BATS.

Abstract:

For 5G and future wireless communications, using millimeter wave and higher frequency is necessary to meet the higher and higher data demands. Integrated-Access-and-Backhaul (IAB) is proposed in 5G to provide a flexible and cost-effective solution to quickly deploy a large number of new base stations. The IAB enabled base stations form a wireless mesh network to provide the wireless access services. The 5G NR, designed for wireless access, can achieve excellent single hop performance, but it does not imply the same for multi-hop performance. In this article, we propose a network coding based solution for the IAB network that can improve the throughput, reduce the latency and also improve the robustness in face of link failure. Our solution, called the BATS Protocol, developed by n-hop technologies, can readily be implemented in the existing IAB protocol stack.

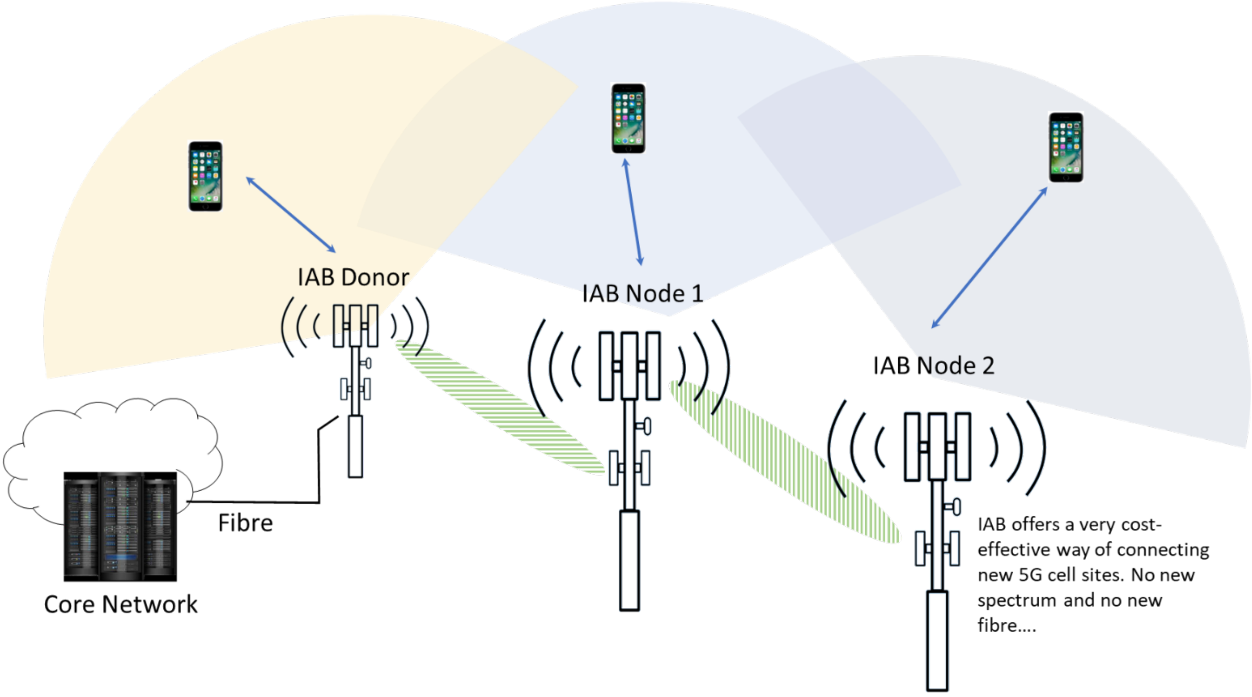
## From Wireless Access to True Wireless Networking

The traditional cellular network is mainly formed by fiber connected base stations, while the wireless communications are mainly used for the access of the users to the base stations. The high throughput connection between the base stations and the core network, called the backhaul, is provided by fiber links. This approach is proven to be suitable for efficiently covering a large area using a small number of base stations.

With the development of wireless communication technologies and the higher demand of wireless data rate, the density of base stations increases by the generation. The traditional wireline backhaul approach, however, is facing more and more challenges due to both the cost and feasibility of deploying fiber. Wireless relaying was first introduced in the cellular network in LTE Advanced [1], where a base station can be extended by a relay node without fiber connection. The relay node in LTE Advanced can only extend the wireless network coverage by at most one hop (i.e., from the user to the fiber connected base station, the data may go through at most one relay node) and has limited functionalities.

Wireless backhauling becomes more sophisticated in 5G with a new feature called integrated access and backhaul (IAB) (defined in Release 16 [2] and enhanced in Release 17 [3]). The game changer is the millimeter wave (mmWave) adopted in 5G to achieve a high data rate [4]. On the one hand, the use of mmWave requires more base stations with smaller covering area compared with the base stations using the sub-6 GHz frequency. On the other hand, the high frequency of mmWave allows a large available spectrum bandwidth to be shared among wireless users for access and wireless backhaul. IAB becomes an attractive solution to quick deployment of a large number of new base stations without the availability of fiber drops, which is essential for mmWave deployment [4].

IAB opens the door for a new generation of the cellular network infrastructure [5]. A tree topology is supported initially with multi-hop backhauling, i.e., an IAB enabled base station can be backhauled to the core network via more than one intermediate base stations [2]. Enhanced IAB with more general multi-hop backhaul network topologies was subsequently proposed [3]. IAB has the potential to be an alternative for wireline backhaul, but it is still new and immature. In the next section, we discuss some major technologies behind IAB and the challenges towards the large-scale adoption of IAB.



IAB offers a very cost-effective way of connecting new 5G cell sites. No new spectrum and no new fibre....

## Technologies and Challenges of IAB Networks

A base station with IAB enabled is called an IAB node, which supports both wireless access of users and wireless backhauling using the same lower layers (e.g., PHY, MAC and RLC) defined in the 5G New Radio (NR) and the same physical spectrum for wireless access. An IAB donor is a special IAB node that has a wireline backhaul connecting to the core network. To form the backhaul network[2], a sequence of procedure is defined in Release 16 for an IAB node to connect to the IAB network and setup the backhaul link. This procedure is similar to that of a user equipment connecting to a base station.

For each IAB node, the backhauling is formed by the multi-hop communication from this IAB node to the IAB donor. Release 16 defines a new Backhaul Adaptation Protocol (BAP) to assistant the backhaul network routing. The downstream flow control is also done with the BAP sublayer. This multi-hop communication is encapsulated as a logical link (called the F1 interface) for the users, so that the wireless multi-hop backhauling is transparent to users.

Essentially, the IAB nodes form a wireless mesh network that provides the backhaul services to the IAB nodes. Compared with the traditional wireline backhaul network, the wireless backhaul network has two major distinct characteristics: 1) The wireless link is not reliable due to fading, interference, blocking and noise; and 2) The wireless links is shared by both access and backhaul, and hence the communication resource is not dedicated for backhauling. These characteristics may result in poor performance of the backhaul network in terms of reliability, latency and availability [6].

The enhancement of IAB in Release 17 proposes the use of multiple donors, topology adaptation, and flow/congestion control for more robust and reliable backhauling. However, the existing IAB specification still has two fundamental weaknesses that may degrade the performance of an IAB network.

First, the lower layer communication (PHY, MAC and RLC) of the IAB network reuses the existing one from the 5G NR. The 5G NR, designed for wireless access, can achieve excellent single hop performance, but it does not imply the same for multi-hop performance. In 5G NR, both the PHY layer and the RLC layer employ retransmission for high link-level reliability, and the feedback delay accumulates in the IAB backhauling and hence increases the end-to-end delay [7]. It has been shown that if the link-level reliability is relaxed, the end-to-end throughput of a multi-hop wireless network can be much higher, and even higher throughput can be achieved using network coding to replace the feedback-based retransmission [8].

Second, the IAB network employs store-and-forward based network layer communication similar to TCP/IP. In the traditional Internet formed by reliable wireline links, the single path routing implied by store-and-forward and the end-to-end congestion control can be argued to be optimal for unicast communications. But the store-and-forward mechanism is not optimal when multiple paths can be employed concurrently or when the network has unreliable links. Both network coding and fountain code based multi-path communication schemes can achieve better performance for the IAB network [7][9][10].

## A Network Coding Solution for IAB Network

We provide a solution for IAB networking based on network coding. The solution is formed by two parts:

- An efficient network coding scheme called BATS code is employed to process the data at both the source node and the intermediate nodes to achieve the network coding gain in a multi-hop, multi-path communication scenario.
- A BATS code compatible flow control mechanism is employed to dynamically control the BATS code parameters hop-by-hop to optimize the network resource usage.

The combination of these two parts is also called the BATS Protocol [8]. Here we first discuss these two parts of the BATS Protocol, and then explain how to embed the BATS Protocol in the design of IAB.

## BATS Code

BATS code, invented by the authors, is the most advanced linear network coding scheme that can achieve close to optimal linear network coding gain with a mild computation cost [11]. The basic version of BATS code comprises an outer code and an inner code. The outer code is a matrix-generalized fountain code. At the source node, the data to be transmitted is encoded by the outer code into a sequence of batches, each of which includes a number (called the batch size) of coded packets of the same length. When the batch size is 1, the outer code becomes a fountain code. The advantage of using a batch size larger than 1 is to allow the application of network coding to the packets belonging to the same batch, which is also called the inner code.

We first use an example in Figure 1 to illustrate the advantage of using the inner code for networks with unreliable links. Suppose the source node has 8 packets to be transmitted through multiple hops to the destination node. Assume that each hop loses 2 out of 10 packets. We can design the following inner code: the source node generates two recoded packets by taking random linear combinations of the 8 packets. All the 10 packets are transmitted by the source node to the first intermediate node. According to the link assumption, the first intermediate node receives 8 packets. The intermediate node does not perform any decoding operations, but instead generates two recoded packets by taking random linear combinations of the 8 received blocks. The same operation is performed by the second intermediate node, so on and so forth. The destination node also receives 8 packets, which are linear combinations of the original 8 packets. The linear transformation of a batch from the source node to the destination node can be conveyed by the coefficient vectors transmitted with each packet. If the inner code uses a large finite field, the linear transformation is of full rank with a high probability and hence the original 8 packets can be decoded.

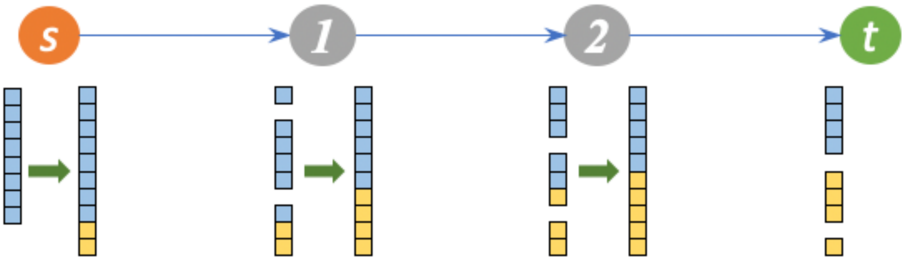


Figure 1: An example of inner coding.

The above example demonstrates that for any number of hops, the destination node can always receive 8 packets. In other words, this inner code achieves the optimal rate for the loss model assumed. However, a practical network would have a random loss pattern, and a non-trivial BATS code is required to achieve a good performance. In general, the number of recoded packets generated at each hop can be different and the linear transformation is not always full rank. The outer code of the BATS code introduces relations among the batches so that the destination node can decode multiple batches jointly to recover the original data transmitted by the source node.

The BATS code can be a systematic code in the sense that the outer code first generates a number of uncoded batches (called the systematic batches) which are formed by non-overlapping segments of the original data. When the network has no loss, the original data can be recovered from the received packets without decoding. When the network has loss, the outer code can generate more batches, which can be decoded with the systematic batches to recover the original data. Moreover, the BATS code can also be a streaming code that encodes a data stream instead of a data block. A streaming code can strike a good balance between delay and reliability.

## BATS Flow Control

All the packets transmitted in the networks when using a BATS code for the end-to-end communication from a source node to a destination node is called a BATS flow. Due to the use of network coding, a BATS flow is fundamentally different from a flow using store-and-forward in two aspects. First, flow conservation is not satisfied for a BATS flow due to the new packets generated by network coding. Second, the end-to-end flow rate is not equal to the packet rate, but is instead quantified by the average rank of the batch transformation. Owing to these two differences, a new flow control mechanism is required for a BATS flow.

The parameters of a BATS flow include the batch rate and the recoding parameters at each node transmitting the batches. The BATS Protocol not only optimizes the flow parameters to maximize the end-to-end flow rate of each BATS flow, but also allocates the network resources among multiple flows to guarantee QoS. Different from the end-to-end flow control mechanism in TCP/IP, the BATS Protocol involves the intermediate nodes in the flow control mechanism. Similar to traditional hop-by-hop congestion control, the BATS Protocol can react faster to traffic fluctuations than end-to-end congestion control.

Due to the forward error correction (FEC) nature of network coding, a BATS flow can readily use more than a single path. For the network example shown in Figure 2, three paths exist from the source node to the destination node. The traditional routing algorithms chooses a single path for the communication from the source node *s* to the destination node *t* subject to a shortest path or lowest latency criterion, for example. The single path routing approach is not globally optimal and is also vulnerable to link failure, which is common for wireless networks. A BATS flow can use all the available links simultaneously: The batches generated at the source node can be transmitted on both outgoing links and node *a* can also transmit its recoded batches on both outgoing links. This way, the transmission rate between the source node and the destination node can be significantly increased.

As a summary, using the BATS Protocol for IAB can achieve better performance in terms of reliability, throughput and latency due to the following features of the Protocol:

- Enable the use of multiple paths simultaneously to gain in both throughput and robustness.
- Reduce the link reliability constraint in multi-hop network communication so that a better AMC and power control mechanism can be employed to improve the link throughput.
- Reduce the latency generated by the link-level retransmission (ARQ) and physical-layer HARQ using network coding.

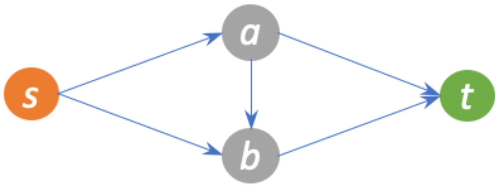


Figure 2: A network of 4 nodes, where *s* is the source node, *t* is the destination node, and *a* and *b* are two intermediate nodes.

## Implementation in IAB

The BATS Protocol by n-hop technologies can be implemented in the IAB nodes in a way that is compatible with the existing IAB framework, making it transparent to the user devices. In the IAB network, a tunnel is set up (using the GTP-U in the F1 interface) between the IAB node directly connected to both the user and the IAB donor. All the IAB nodes employ the Backhaul Adaptation Protocol (BAP) to support the routing in the IAB network. See Figure 3 for an illustration.

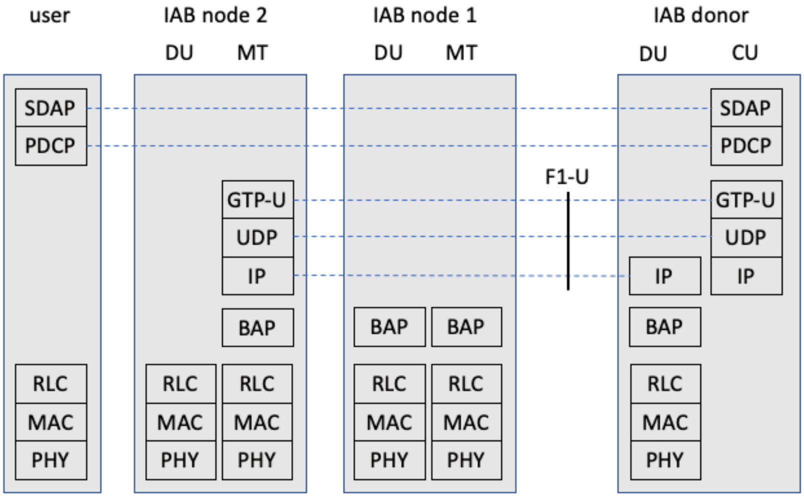


Figure 3: The existing IAB user plane protocol stack.

In this framework, the BATS Protocol can be implemented between the F1 interface and the BAP. The outer code is only applied at the IAB node directly connecting the user and the IAB donor, similar to the F1-U interface. The inner code is applied at all the nodes, similar to BAP. See Figure 4 for an illustration of the BATS Protocol.

To benefit from the BATS Protocol, the existing BAP, RLC, MAC and PHY can be tuned to improve the overall system performance.

- For BAP, the packets of multiple incoming links of a BATS flow can be merged, and the packets of a BATS flow can be transmitted on multiple outgoing links.
- For RLC, retransmission is not necessary (as the inner code plays a similar role), which may reduce the delay incurred by ARQ.
- For PHY, more aggressive AMC can be used to achieve higher throughput without the link-by-link reliability requirement. Power and HARQ can also be optimized by taking the network coding into consideration.

Moreover, the bandwidth sharing between the access and the backhaul should be jointly optimized by the BATS Protocol to achieve the optimal performance.

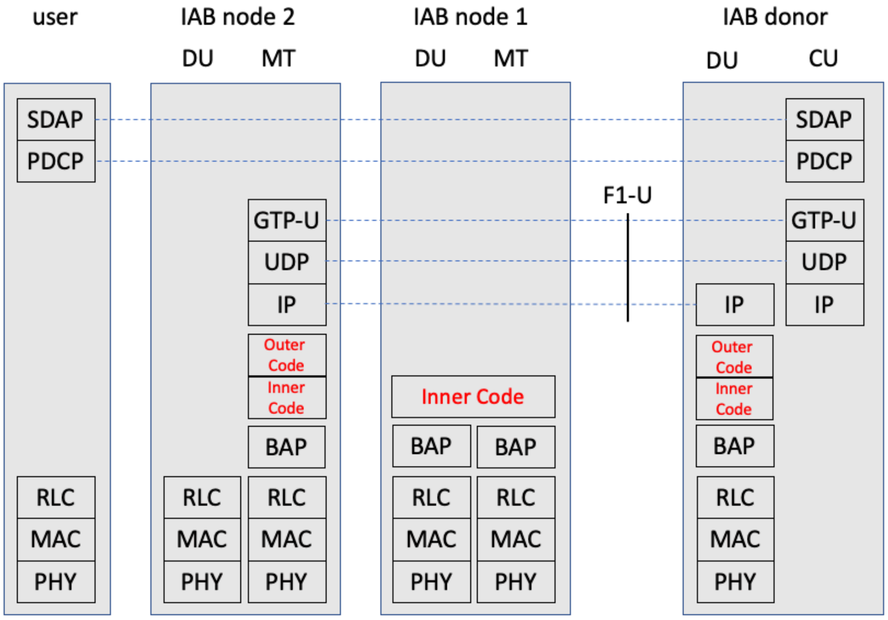


Figure 4: Illustration of the BATS Protocol in IAB.

In the future, it is also possible to further extend the concept of IAB in two directions: First, implement the BATS Protocol in the user devices so that the IAB nodes only need to apply the inner code. Second, enable a core network formed by base stations connected by wireless links, which may find industrial and V2X applications. By these extensions, the end-to-end communication between users can be supported by the BATS Protocol. See Figure 5 for an illustration of this placement of the BATS Protocol.

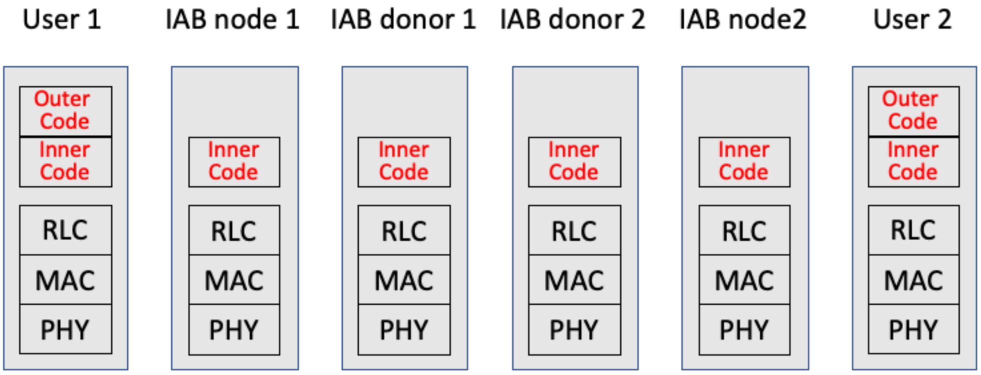


Figure 5: Illustration of the BATS Protocol at the user devices.

## Enquiry

For enquiry about the BATS technology, please send email to info@n-hop.com

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