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Efficient network coding-based data transfer framework for multihop wireless communication

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Abstract: With the growing demands of wireless applications and mobile data connections, wireless communication is expected to provide the ever-increasing demand for higher data rate and efficient data communication. Energy is also one of the hot issues needed to be considered for future wireless networks. In this paper, an efficient network coding-based data transfer (E-neco) framework is developed to achieve more energy-saving and bandwidth-efficient data communication for data transmission, data collection and data sharing services. For these data transfer applications, we propose new network coding-based transmission schemes and medium access control protocols. Topology and network coding techniques are utilised in the framework. This is a conceptual framework developed for future generation wireless communication such as multihop communication, massive machine communication, device-to-device communication and new techniques can be added to support future demanding services. Simulation results reveal an improvement in terms of throughput, latency, fairness, energy consumption and network lifetime.

Keywords: multihop wireless communication; network coding; medium access control protocol; data transfer framework; energy efficient protocols; wireless network topology; future wireless networks.

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1 Introduction

Information and communication technologies (ICT) have contributed to the social and economic development of many countries these days and world's business model is also transforming to digital. A digital economy is rapidly replacing the whole world's economic system and it has strong impact on the economic and social development. In addition, the societal development leads to the changes in the way mobile and wireless communication systems are used. The growth in global consumer mobile services such as mobile banking and commerce, mobile social networking, mobile gaming, mobile email, mobile music and video will surprisingly increase by 2020 according to the estimation of Cisco® visual networking index (VNI) (Cisco, 2016). The traffic from wireless and mobile devices will become 78% of internet traffic with only 22% from wired devices.

Moreover, the expectation of future wireless applications includes very high demand of high data rate, high availability, and low latency for applications such as media streaming applications and healthcare systems. The scalability and flexibility are also important due to the existence of a large number of connected devices with diverse applications. The challenge is the trade-off between satisfying the requirements and the growing cost. Efficiency and scalability becomes the key design criteria (Osseiran et al., 2014).

The current trend and challenges of future generation wireless communication are motivating the researchers and the industry for the new revolution Fifth Generation mobile technology, 5G. The 5G is viewed for providing communication and data services using all possible access solutions and core network switching rather than a new radio access technology. Cooperative communications and network coding (NC), full duplex, massive multiple input and multiple output (MIMO), device-to-device (D2D) communications and green communications are some of the promising techniques for 5G (Ma et al., 2015).

NC and D2D communications have high potential to be integrated to the 5G technologies due to the fact that the growing number of devices to be connected in the future. D2D communication creates a market potential for new services and new approaches as it can provide end user benefits such as reduction of power consumption, increase in throughput, and operator benefits such as spectrum efficiency and extension of coverage (Pahlevani et al., 2014). Due to the advantage of dense network of wireless devices and popularity of various wireless applications, multihop relaying becomes the way of communication for future again.

There are many popular scenarios that are branches of multihop wireless communication such as mobile ad hoc networks (MANET), wireless sensor networks (WSN), wireless mesh networks, and vehicular ad hoc networks with their own specific characteristics. Although each wireless device is equipped with cellular or Wi-Fi interfaces, it also possesses Bluetooth, which is not as frequently used as cellular or Wi-Fi interfaces for communication purpose except for sharing files between two nearby devices. Nowadays, nearly everybody has a mobile phone in his/her pocket while commuting outside or working inside the building. Therefore, there is a high chance of connectivity for communication among these existing dense wireless devices.

1.1 Requirements of future generation networks and challenges

The world is leading to build the connected devices, not limited inside the industries but smart streets, smart supermarkets, smart homes and even smart cities due to the advancements in internet of things (IoT), computation and communication technologies. The growing demands of wireless applications, massive deployment of sensors and actuators will become a typical application. In this scenario, connectivity and longer battery lifetime are requirements for the collection of updated data from the physical environment.

Communication is also expected to provide the increasing demand for higher data rate and to be efficient. The traditional way of reliable communication is based on the retransmission of packets and acknowledgements. It costs bandwidth and high latency for high number of retransmissions to achieve the successful data transfer. Mobile terminals in wireless systems also have energy limitation. Although the constraints on computation and storage can disappear with the development of fabrication techniques, energy limitation will still be an issue (Wu et al., 2012). Therefore, achieving high data rate with low energy consumption (Mbps/Joule) becomes one of the main problems for the future wireless communication.

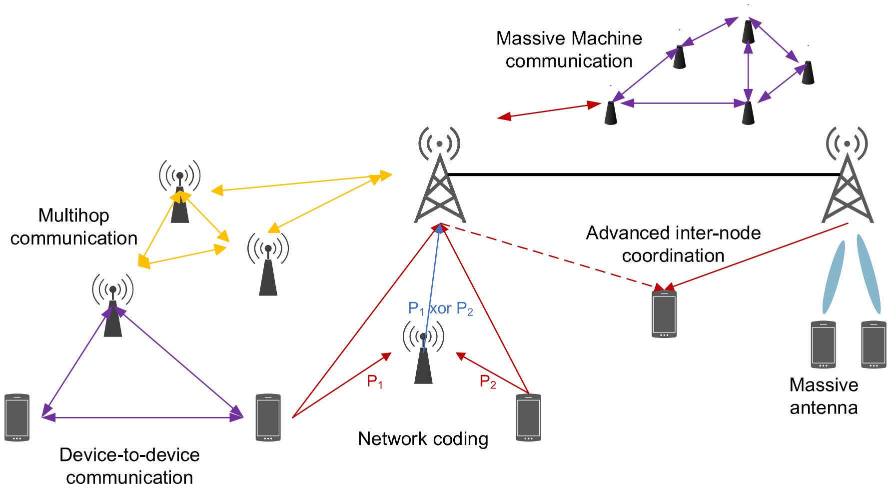
Another scenario which has high prospect for future is requirement of stable connectivity in very crowded places. Due to the increase number of connected devices to the IP network and high data rate services such as video streaming and file downloads, the traffic volume is very high and leads to network overload. As a result, users suffer from service denials. In this case, if the burden on network can be shared by the nearby wireless devices by creating a cooperative data sharing group via the built-in Bluetooth or Wi-Fi interfaces, the service denials will be reduced.

With this approach, devices possess a faster and reliable short-range communication service to achieve their needs without any request to a far base station (BS) again. The network overload can also be reduced and BS will be able to serve other users. However, the challenges are high. Network should provide scalability and flexibility to a large number of connected devices with diverse application purposes in very low complexity for long battery lifetimes.

These scenarios are illustrated in Figure 1. The figure is originally from the mobile and wireless communications enablers for the 20-20 information society (METIS) project

(Osseiran et al. 2014). METIS also believes wireless network coding and buffer-aided relaying to be the promising research directions in multi-node/multi-antenna transmission.

Figure 1 Multi-node/multihop communication (see online version for colours)



All the scenarios include multihopping as a common communication paradigm. This paradigm is currently not a main option in IEEE 802.11 standard due to its remaining issues such as high latency and its effect to throughput improvement. However, there is a high chance to become a core communication paradigm in future because of the dense usage of wireless devices and the new techniques such as wireless NC. It can be setup in ad hoc fashion or via infrastructure such as cellular stations. Multihop relay-based communication is gaining global acceptance as one of the most promising technologies in next generation wireless cellular networks with the performance expectations such as throughput improvement, extension of coverage area and decrease of energy consumption (Shen et al., 2009; Loa et al., 2010). NC techniques can be integrated into the relay-based multihop wireless networks (MWN) to reduce the remaining weaknesses and can benefit the remaining issues of multihop wireless communication. For the above reasons, our research specifically focuses on the multi-node and multihop communication among the very diverse technologies to achieve the performance and capability targets of 5G wireless systems.

1.2 *Multihop wireless communication and research issues*

In MWN, nodes communicate with each other using wireless channels and do not have common infrastructure or centralised control. Any two nodes can communicate directly if their packets can be correctly decoded under the desired signal-to-interference-plus-noise-ratio (Lu et al., 2012). In order to communicate with nodes beyond their range of transmission, a wireless node has to depend on other intermediate nodes for relaying its messages to the desired destinations. Such architecture requires that nodes in the network play the role of a source, a destination, or a router to relay the messages.

MWNs also have many important challenges. Determining a routing function for sending packets to the intended destination is one of the main challenges because of the characteristics of unreliable wireless links, packet loss and topology change. The routing protocol finds the path between the source and destination depending on the available links and intermediate nodes in the network. Long links can reach the destination in few hops, but at some low speed. On the other hand, the short links can support the transmission in high rate, but more hops are needed to reach the destination. As a consequence, the chance of a node to be involved in relaying the other's data packets becomes high (Awerbuch et al., 2004). Therefore, the level of congestion at an intermediate node becomes an important issue and lead to problems such as high energy consumption and buffer overflow of the node. Moreover, the energy of each node is limited and the overhead for each single packet transmission will cost more communication resources when multiple relays are involved for each active data flow.

Multihop communication has strong background and has been researched about the relay-based transmission (Pabst et al., 2004). However, there are some remaining issues. Due to operation in half-duplex manner, there is inefficiency in spectrum usage. Multiple time slots are required and consequently, it effects the throughput improvement. Another problem introduced in multihop communications is the latency. Relay-based communication also consumes communication resources as more hops are needed. More researches are needed to find out more solutions which are efficient, reliable, less energy consumed and able to provide the demand of today's wireless applications.

Emergence of wireless NC techniques has brought a new life to the relay-based solutions. Wireless NC allows the intermediate nodes to combine the packets for multiple independent communication flows with no extra cost because of the broadcast nature of wireless transmission. The advantage of NC is reduction in the number of transmissions without affecting the recovery of original messages at the destination nodes. NC has high potential to be integrated into future generation wireless networks to increase throughput and to save energy and bandwidth resources.

Communication protocols should not be built in the usual way by looking at a single communication flow at a time, but rather multiple communication flows should be processed jointly. The new challenge is the proper combination of NC techniques with multihop relay concept for the scenarios discussed in requirements of future generation networks. In this paper, we investigate how the benefits of NC can be utilised in MWN to provide efficient data communication and to fulfil the requirements of future generation networks.

1.3 Contributions

Aiming to find solutions for future wireless networks, this paper focuses to investigate the potential benefits of NC to provide efficient data communication in multihop wireless communication networks for data transmission, data collection and data sharing. The main contribution of the paper is a data transfer framework for the communication in multi-node MWN. We propose a data transfer framework called efficient network coding-based data transfer (E-neco) framework which includes three schemes: network coding-aware medium access control (necoMAC) scheme, network coding-based data gathering (necoDG) scheme for WSNs and balanced cooperative coding and transmission with physical layer network coding (BCCT/PLNC) scheme for high rate data exchange with low power consumption between a cellular BS and its mobile stations. The proposed protocols are for hop-by-hop communication in link layer of protocol stack.

This contribution is a combination of three different data communication schemes as a data transfer framework with the help of wireless NC and multihop wireless communication. The advantage of this framework is that three different processes of data communication can be performed in a more flexible way to achieve higher efficiency and reduce energy and bandwidth resources.

Another contribution is the design of new protocols and algorithms for incorporating NC techniques to work properly with the existing characteristics of the networks for each data transferring scenario. It also finds a way of applying the main methodologies such as:

1. relay-based higher-quality path selection mechanism such as 2PSP
2. specific topologies for NC such as golden chain and golden triangle
3. technologies based on relaying, multihopping and wireless NC such as RLNC and XOR to achieve the goals in a simpler and flexible way.

This work can contribute to the study of incorporation of NC techniques with IEEE 802.11 MAC scheme for different data communication scenarios.

Due to this framework, wireless NC and multihop communication can provide more performance improvement such as throughput increase, bandwidth saving, energy reduction, and thereby extending the network lifetime.

2 Related work

NC (Ahlswede et al., 2000; Fragouli et al., 2006) is a technique which can be applied at a source or at an intermediate node to create new outgoing packets by some mathematical functions. Processing the data packets can replace the traditional ‘store and forward’ paradigm at an intermediate node by performing binary addition of bit streams at the network layer or by superimposing incoming signals at the physical layer.

The application of NC into layer 2 of OSI reference model appears in Gaddy (2016). In their work, NC is integrated into the 802.11 infrastructure by adding a sublayer of NC functionality between layer 2 and 3 of the seven- layer stack (Zimmermann, 1980). It combines layer 3 datagrams at access points (APs) and layer 2 broadcasting is performed. They showed that Layer 2.5 NC works best in high-rate symmetric traffic flows between two clients connected to the same 802.11 AP. It can be observed that symmetric traffic flows and high rate are essential to gain benefits from using networking coding at AP. In our proposed NCA-2PSP protocol, we also apply this observation. NC functionality is applied at the relay node identified by the 2PSP mechanism, which finds the high-rate links.

Another research issue relating to NC and medium access control is due to the fairness of DCF mechanism in IEEE 802.11 standard (Committee, 1999). To achieve the highest benefit from network coded packets/frames, they need to be transmitted with a higher priority than the normal packets/frames. This issue becomes very clear when (Katti et al., 2008) proposed the first practical inter-session NC approach called COPE for the networks with perfect links.

COPE combines IEEE 802.11 DCF with XOR NC technique. It adds a layer of NC between the network layer and MAC layer. The relay node transmits the XOR-coded packets and reduces one transmission time slot like in our proposed NCA-CSMA protocol. As COPE relies on the DCF operation of IEEE 802.11, relay node needs to compete the channel access with other nodes to transmit the coded packet. Therefore, performance of NC opportunity is totally depending on DCF and is limited by DCF. We design carefully our proposed protocols to avoid this limitation.

To solve the above issue, Huang et al. (2010) proposed a combination of NC with CSMA/CA protocol to enhance the fairness of wireless medium access among stations for a single-relay networks. Their approach is optimisation of the minimum contention window size according to the number of stations to create appropriate transmission opportunity. But this approach also has efficiency limitation when the number of competing stations increase.

To solve the limitation of DCF on the NC opportunity, Palacios et al. (2014) introduced a coding-aware MAC scheme. This scheme enables the reverse direction (RD) communication between the relay node and any other station. Upon successful reception of a data packet the relay station can transmit a coded packet whose destination is the source of the received packet. The relay station can reduce the channel contention and the coded packet can be sent right after a packet is received. The value of the duration field in the transmitted data packet is extended to cover the channel access for the duration of transmission in RD. Therefore, the throughput, delay and energy saving can be improved. Only when the channel condition is poor, this RD transmission will lead to the retransmission of both the forward and reverse data because the reverse transmission is used as an implicit ACK and the packet loss probability is higher for a data packet than for an ACK packet.

Overhead of control messages is also an important issue for the protocol design in combination of NC and MAC protocol. COPE tried to reduce the overhead control messages in its transmission cycle. It saves one transmission for ACK message after receiving the coded packet by a source node. This ACK event will be added in the header of next coded packet to acknowledge the packet reception.

Relating to the NC-based data gathering, energy-efficient operations are classified into three main groups. They are in-network data aggregation and data compression technique, routing protocols, and structure of nodes working together. Among them, structure of working nodes includes tree, cluster, or centralised approach. Cluster-based approach has many advantages. A number of clustering algorithms have already been designed for the WSNs in the literature depending not only on the network architecture but also on the characteristics of the cluster head (CH) nodes (Gupta and Younis, 2003; Younis, 2004). Clustering can save communication bandwidth as the member sensors of a cluster only communicate with the CH and avoid interactions with other clusters.

Although many data aggregation techniques and routing protocols are designed for a number of performance metrics such as energy efficiency, reliability, quality of service, etc., there is an important issue relating to the energy efficiency of data gathering. It is the error and loss in wireless communication due to the dynamic channel conditions. It is important to provide reliable communication to improve network lifetime of sensor networks.

The traditional way to provide the reliability is to use the feedback messages to report the received or lost packets. However, these feedback messages consume bandwidth and energy. Energy-efficient error control techniques to prolong network lifetime in resource limited network and wireless communication remains a challenge (Salija and Yamuna, 2015).

Low energy adaptive clustering hierarchy (LEACH) (Heinzelman et al., 2002) is a protocol architecture for microsensor networks that combines the ideas of energy-efficient cluster-based routing and media access together with application-specific data aggregation to achieve good performance in terms of system lifetime and latency. Zhao et al. (2012) improve LEACH and its dependent works by introducing a vice CH which takes over the role of CHs instead of rebuilding the clusters from the beginning. That improvement diminishes the frequency of reclustering and prolongs the time of being in steady-state phase, which prolongs the lifecycle of the whole network.

In our proposed scheme, necoDG, we add NC functions at CHs and intermediate nodes on the way to CHs to provide reliable communication from errors and to reduce bandwidth and energy usage for the retransmitted packets like in Razzaque et al. (2014). The network architecture is basically cluster-based networks due to its advantages, for example, sensor nodes only communicate within their cluster and avoid direct communication to a far BS. By this approach, network traffic at BS (sink) is separated to each cluster and management of resources such as channel access will be more efficient.

The scenario of cooperative data sharing group has been considered in El Rouayheb et al. (2010a), Médard et al. (2012), Heidarzadeh and Sprintson (2015), and Keshtkarjahromi et al. (2015). The goal is to fulfil the requirements of all participants in the group with minimum transmissions. The encoding scheme that will minimise the number of transmissions is referred to as index coding (Chaudhry and Sprintson, 2008), where a central BS performs the transmissions of linear combined packets to other clients. In this category, many existing research work such as El Rouayheb et al. (2010b), Tajbakhsh and Sadeghi (2012), Courtade and Wesel (2014) and Sui et al. (2016) mainly studied the optimum number of transmissions to reduce the complexity, overhead and delay until all clients ultimately recover the required packets. They formulated the problem into integer programming and proved that it is NP-hard. With linear NC (Fragouli et al., 2006), benefits of cooperation can be further considered for the data exchange problem because many devices can simultaneously gain from one linearly coded packet (linear combination) transmission.

El Rouayheb et al. (2010b) formulated a lower and upper bound on the number of transmissions needed to satisfy the requirements of all members of the group and showed that their algorithm performs closer to the lower bound. The minimum number of transmissions is greater than or equal to $n - n_{min}$ where n is the number of packets and n_{min} is the minimum number of packets held by a member, i.e., $n_{min} = min_{1 \leq I \leq k}\, n_i$. If all clients initially have the same number of packets $n_{min} < n$, i.e., $n_i = n_{min}$ for $i = 1, \cdots, k$ clients, then the minimum number of transmissions is greater than or equal to $n - n_{min} + 1$. The upper bound on the minimum required number of transmissions is less than or equal to

$$\min_{1 \leq i \leq k} \left\{ \left| \overline{X_i} \right| + \max_{1 \leq j \leq k} \left| \overline{X_j} \cap X_i \right| \right\} \tag{1}$$

for $|F| \geq k$. Each client c_i initially holds a subset X_i of packets in $X = \{x_1, \cdots, x_n\}$, i.e., $X_i \subseteq X$. And $n_i = |X_i|$ denotes the number of packets initially available to client c_i, and $X_i^{\overline{\ }} = X \setminus X_i$. The authors choose a candidate that possesses the maximum number of received packets as a transmitter for next round. If there are more than one candidate client, their scheme chooses the next transmitter randomly.

We consider fairness on the number of transmissions each client makes and also maintain the minimum number of transmissions as a whole in our work. The reason is to balance the responsibility of transmission from each client and to maintain energy saving for each individual participant. Like in the case of necoDG, the responsibility as a CH is rotated among the members of a cluster to avoid the energy depletion of a certain device. If a particular device with an independent packet runs out of energy quickly, other devices will not satisfy their needs and the data exchange process cannot accomplish.

3 E-neco framework

An E-neco framework is a conceptual framework developed for transferring data between wireless stations in wireless communication scenarios discussed in Section 1.1. This framework is based on the concept that aims for future potential network technologies such as D2D, machine-to-machine (M2M) and MWN to be able to provide the high-rate low-energy, fast and reliable services to the billions of connected devices.

The general architecture of E-neco framework is depicted in Figure 2. The framework utilises network topology and NC techniques with MAC protocols. Therefore, the focus of this framework exists at data link layer. It consists of three main components:

1. data transfer mode
2. topology
3. medium access control protocols.

The functions of each component are briefly described as follows:

- Data transfer mode: Three types of data transferring process can be accomplished by the framework. They are:
    a. Data transmission: transmission of data from one node to another.
    b. Data gathering: collection of data from many nodes, e.g., data gathering in a WSN.
    c. Data sharing: distribution of possessed data to other members in a group for a common welfare.

  The specific data transfer process is configured by the user at this moment. In future, we can use a traffic pattern to activate the selection of the three processes.
- Topology: way of connecting links between nodes for NC opportunity.
    a. Golden topology: types of topologies that creates NC opportunity are called golden topology. They consist of chain (also called linear) topology, triangle, diamond, Y-topology and cross (X) topology.
    b. Group formation: formation of logical connection among the participants in a group for data sharing purpose.
- Medium access control protocols: rules by which a frame is transmitted onto the link. The proposed MAC protocols are designed to get maximum benefits from

incorporation with NC. They include necoMAC, necoDG and BCCT schemes for three data transfer modes.

a necoMAC: NC-aware MAC scheme. This necoMAC (Lin et al., 2016) scheme is intended for the data transmission in multirate MWN. NC-aware 2-hop path selection protocol (NCA-2PSP) and NC-aware carrier sense multiple access (NCA-CSMA) protocols are proposed for golden chain and triangle topologies. High throughput, less energy consumption and low delay services are expected from this scheme.

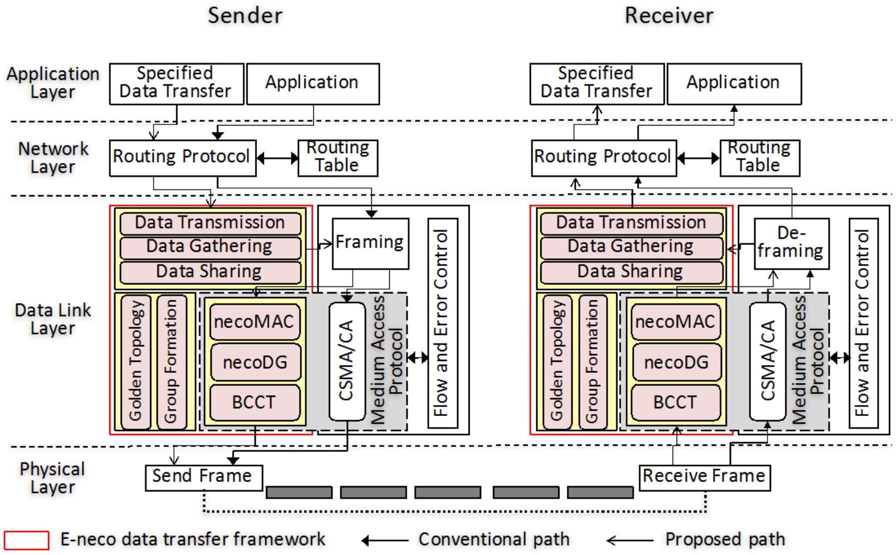
b necoDG: NC-based data gathering scheme for data collection from physical environment such as WSN. NC is applied at the CH or aggregator and at a relay inside a cluster of sensor nodes to assist reliable data transfer to the BS. A modified 2PSP protocol is proposed to achieve more energy saving and longer network lifetime.

c BCCT: balanced cooperative coding and transmission scheme. A NC-based cooperative data sharing scheme in mesh network topology. This scheme is proposed to satisfy the requirements of mobile data users downloading from a congested BS. Local group formation and network coded sharing is the main mechanism in this scheme. Participants are controlled by themselves using the reception information to maintain fairness and network lifetime.

d CSMA/CA: carrier sense multiple access with collision avoidance. The CSMA/CA protocol is one of the two modes of the IEEE 802.11 MAC protocol, which uses the distributed coordination function (DCF) based on the RTS/CTS handshaking mechanism (Kumar et al., 2006). This protocol works in combination with a binary exponential backoff (BEB) algorithm. Before sending data packets, a node first senses the medium for an idle channel in distributed inter frame spacing (DIFS) period. The node delays its own transmission by a random backoff timer and waits for transmission to avoid a collision. The proposed scheme also works compatibly with CSMA/CA protocol.

These three components are relying on each other to perform a specific data transfer. Although they are depicted as separate components for easy understanding, in practice, their functions cannot be separated from each other. Depending on the desired data transferring process, the different topology and medium access control protocols are used. For example, BCCT scheme is selected for the balanced cooperative data sharing with the group formation mechanism of BCCT in mesh topology. The desired topology is created on the fly by the protocol. Therefore, topology and group formation can also be defined as part of the protocol. These two components have very close relation to each other. We describe topology and group formation as a separate component from MAC protocols in our framework. This is to highlight the importance of topology for NC benefit and thereby for improving the performance of the system as a whole.

Figure 2 E-neco data transfer framework (see online version for colours)



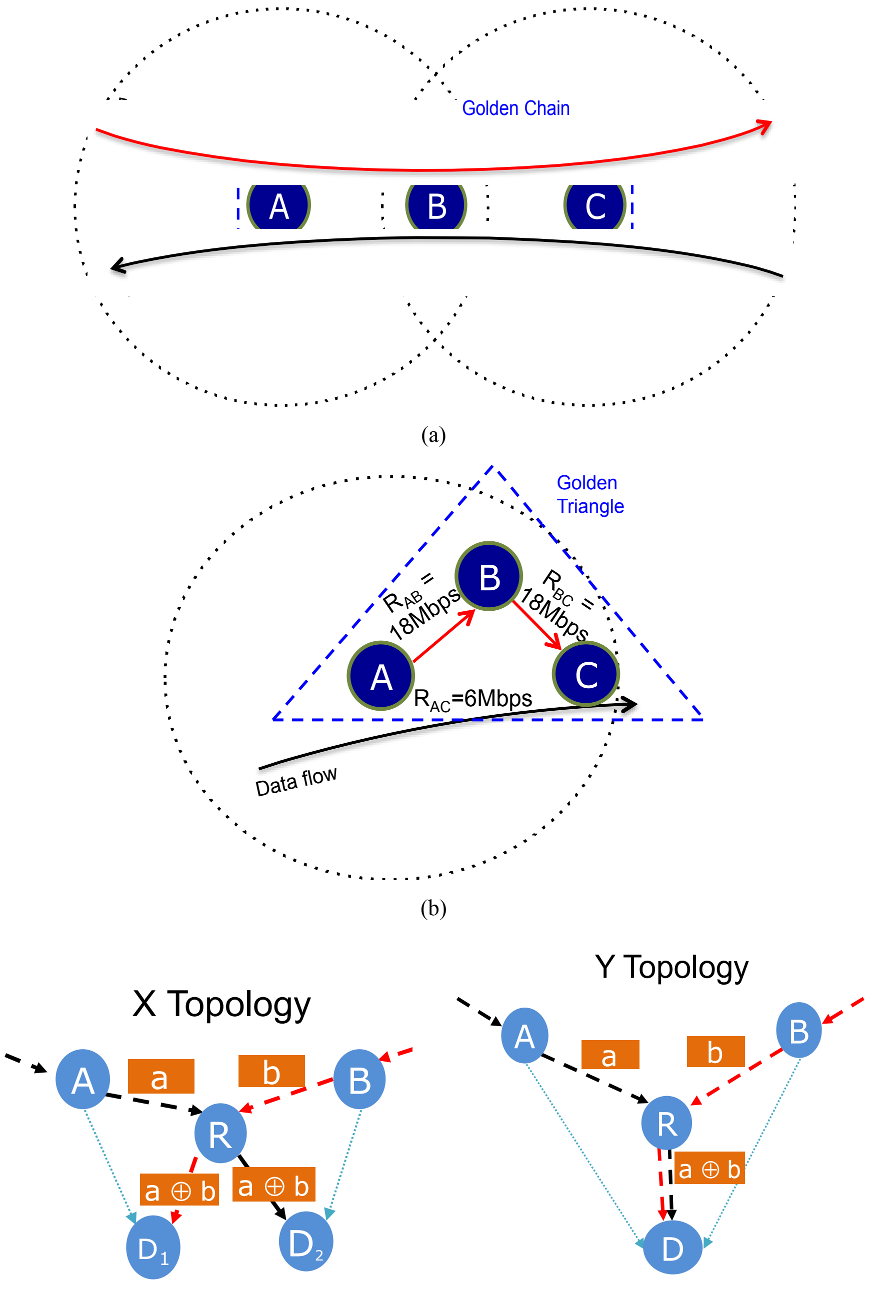
3.1 *Topology and group formation*

Topology and group formation mechanisms play important roles for the improvement of system performance. One of the three main components of E-neco data transfer framework is topology component. This framework focuses on the utilisation of NC at the link-level data transfer operations. There are limitations of NC opportunity at network layer to achieve the maximum performance because the actual transmissions can only happen when the medium is occupied. Therefore, medium access control influences the network coded transmission. Topology influences performance of NC regarding several important metrics. It also affects the performance of control algorithms for scheduling of transmissions, routing, and broadcasting in an ad hoc network (Anjana et al., 2010). The NC opportunity also depends on topology where the source, relay and destination form a specific structure in wireless networks. For example, relay node performs XOR NC to combine some packets in its incoming buffer based on the information of its neighbours. There are certain types of structures called golden chain (two-way relay channel), golden triangle (relay channel), cross and Y topologies (multiple access relay channel) from network perspective. Another type of useful topology for group formation and connections among group members is mesh topology.

3.1.1 *Golden chain and golden triangle*

The two golden topologies are mainly utilised with the XOR NC in our work. A golden chain is defined as a chain of three successive nodes with two data flows from opposite directions. Figure 3(a) shows a golden chain. The two data flows, 1 and 2, forms a golden chain at nodes A, B and C, where A and C are outside the transmission range of each other.

Figure 3 Certain types of topologies that can support NC opportunity, (a) golden chain (b) golden triangle (c) 'X' topology (cross topology) (d) 'Y' topology (also called as multiple access relay channel, MARC) (e) mesh topology for BCCT scheme (see online version for colours)



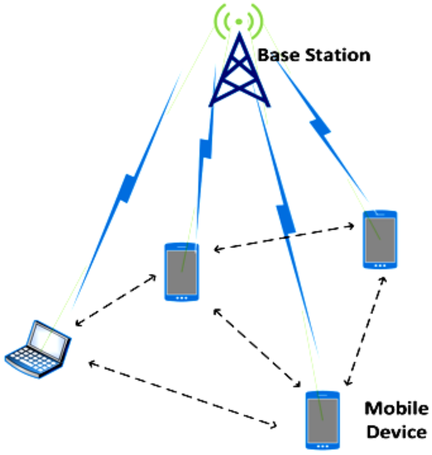
(a)

(b)

(c)

(d)

Figure 3 Certain types of topologies that can support NC opportunity, (a) golden chain (b) golden triangle (c) 'x' topology (cross topology) (d) 'y' topology (also called as multiple access relay channel, MARC) (e) mesh topology for BCCT scheme (continued) (see online version for colours)



(e)

For a golden triangle, A and C are within the 1-hop transmission range of each other. They may have a low-rate link between them due to the far distance. The main property of a golden triangle is the relay node which helps transmission in some higher rates. The difference from a golden chain is that a golden triangle does not necessarily require two data flows. It can work with one direction data flow as depicted in Figure 3(b).

3.1.2 X, Y and mesh topologies

'X' and 'Y' topologies are depicted in Figures 3(c) and 3(d), respectively. In both cases, the two data flows from node A and B pass through an intermediate node R to the destinations D_1 and D_2 in Figures 3(c) and to a common destination D in Figure 3(d). Node R can process NC operation over two incoming flows a and b and transmit the coded packets $a \oplus b$ to the destinations. The destination nodes have high chance to overhear the transmissions from the nearest senders without additional transmission cost and copies of those messages are useful for the recovery of original messages. By this method, the intermediate node accomplishes the forwarding of received messages in fewer number of transmissions and saves energy and bandwidth consumption.

In mesh topology Figure 3(e), there are direct connection links between every station. Wireless devices can utilise the advantage of short-distance communication links by creating a cooperative data sharing group among them via the built-in Bluetooth or Wi-Fi interfaces. This can be formulated as a NC and transmission scheme. For example, some nearby wireless end devices such as mobile phones can benefit a fast downloading service from a common BS by cooperating to exchange their packets in mesh topological connections.

3.2 Proposed necoMAC scheme

The proposed necoMAC scheme is for the efficient data transmission in high rate by using the relay and multi-rate capability of physical hardware. It comprises various mechanisms such as data communication mode, topology management and MAC protocols for data transmission. MAC protocols include 2PSP, NCA-2PSP, NCA-CSMA and CSMA/CA protocols. If only one incoming data flow exists at a node and a golden triangle can be created with the help of a relay, data transmission will occur in 2PSP. If the intermediate node detects two incoming data flows from opposite directions, the transmission in NCA-CSMA will occur. This applies XOR NC over two data flows and broadcasts the coded data frame after a new control message called ready-to-broadcast (RTB). RTB is a modification of RTS which includes the addresses of two receivers in its header field. The data transmission will occur in the conventional CSMA/CA protocol if both golden triangle and chain do not exist.

3.2.1 NCA-CSMA

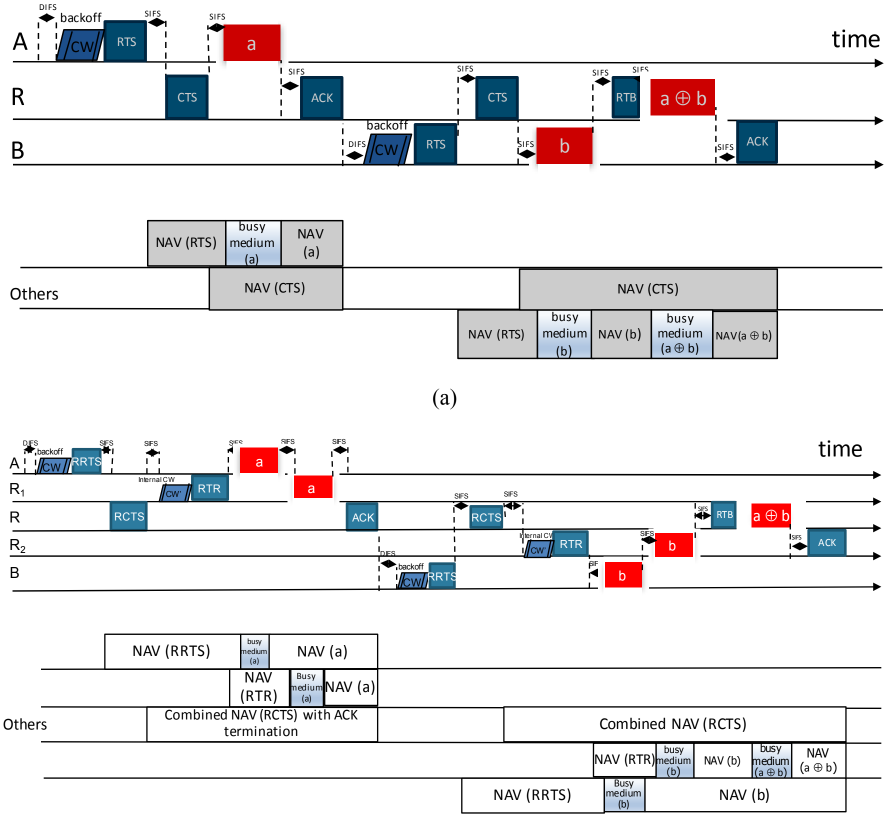
NCA-CSMA is for the data transfer in a golden chain. As nodes A and B are outside the transmission range of each other, the relay node, R forwards the data packets from both A and B by using the XOR NC. The operation of control message handshaking and data transmission procedures of NCA-CSMA protocol is shown in Figure 4(a). The XOR-coded packet is transmitted after a short control message called RTB, ready-to-broadcast from the relay R. This message is shorter than the normal request-to-send (RTS) message. Although the relay sends RTB message, the medium allocation for the relay is already allowed by the protocol like in the case of reversed direction transmission. Therefore, both A and B can receive the XOR-coded packet in one time slot directly after a short time of B's transmission. Data exchange between A and B is completed within three transmissions and energy for one transmission can be saved.

3.2.2 NCA-2PSP

The proposed NCA-2PSP protocol can be applied when two nodes on a golden chain possess a helper relay between them and both of them have some data packets to be exchanged. NCA-2PSP is designed based on the 2-hop path selection protocol (2PSP) (Lim and Yoshida, 2007) and NCA-CSMA. In 2PSP, the authors proposed a relay mechanism and a new contention window called a short backoff internal (SBI). A potential node that succeeds as a relay is allowed to send a ready-to-relay (RTR) message before transmitting payload data from the sender. The RTR message contains the information about a pair of higher transmission rates for the payload transmission.

The three new control messages called relay-request-to-send (RRTS), relay-clear-to-send (RCTS) and ready-to-relay (RTR) are defined. The DCF operation procedures of NCA-2PSP are as follow [Figure 4(b)]. When a node wants to send a data packet, it first waits for the DIFS + BO time period before it can transmit the data. After the sender can access an idle channel, it transmits a RRTS message. If the receiver receives the RRTS message correctly, it replies a RCTS message to the sender. A relay node that hears these control messages determines a suitable pair of higher data rates based on the signal strength of the receiving RRTS and RCTS messages. The relay node decides whether to help the sender or not by estimating the energy consumption of direct transmission and the transmission with the help of relay based on the new estimated rates.

Figure 4 Message handshaking procedure for a data exchange between two nodes via a relay in a golden chain, (a) NCA-CSMA (b) NCA-2PSP with two triangles (see online version for colours)



(a)

(b)

If the relay decides there are more benefits by its help, it broadcasts a RTR message after waiting for a random SBI period. This message contains information about the selected rates that the sender and receiver should use when they send their data packets. If the sender cannot hear any response after SBI interval times out, the sender will transmit the data packet according to the standard DCF procedure. If the sender can correctly decode the RTR message, it will transmit its data packet with the new data rate defined in the RTR message. After the relay node R receives the data packets from sender A and B, it creates a XOR-coded packet of $a \oplus b$ and broadcasts the coded packet. As both A and B are within one-hop transmission range of R, both of them can receive the coded packet and can recover the data packet of each other by doing the XOR function of their own packet and the receiving coded packet. After the data packets are successfully decoded, the ACK messages are sent. Neighbour nodes that hear the ACK shall terminate their

NAV and are free for medium access. The handshaking finishes when the sender receives the ACK message from the receiver node. The functions of R_1, R_2 and R represent the functions of a relay node although they are separately depicted in the figure for the easy explanation.

3.3 Proposed necoDG scheme

The proposed scheme is for data gathering from the physical environment like in a WSN, where there is a sink node (BS), which is the destination of all the other sensor nodes in the network. As it is a part of the efficient data transfer framework, data transmission process from source nodes to the sink, through many intermediate nodes, is more emphasised rather than the data aggregation functions at a CH or at the sink. The transmitted data packets are either the raw data packets from the sensor nodes or the aggregated ones at a CH node. The role of NC in this scheme is to support the communication to be more reliable and to reduce errors and loss.

Sink is a node that connects an infrastructure network with high computing or storage resources, and one or more CHs. The number of clusters depends on the clustering algorithm like the one in LEACH and the number of sensor nodes inside the network. Our emphasis in the proposed scheme is the data transfer in an efficient and reliable way rather than the clustering functions. Therefore, the proposed scheme allows CHs to communicate the sink directly or through a relay node based on the modified 2PSP protocol.

CHs encode incoming packets from different sources into a packet of the same size but can carry much more physical information by the random linear network coding (RLNC) (Ho et al., 2006). Then, these coded data packets are forwarded to the sink and the sink will only acknowledge when the original messages are recovered successfully. In order to recover the original messages in fewer transmissions of coded packets, we add an extra transmission from the relay after a normal 2PSP handshake procedure. More redundancy in the transmitted coded packets can improve the reliability of communication, and the overhead for feedback messages due to packet error and loss can also be reduced due to this scheme. The number of packets being coded together is different from time to time depending on the number of packets received at a CH from sensor nodes.

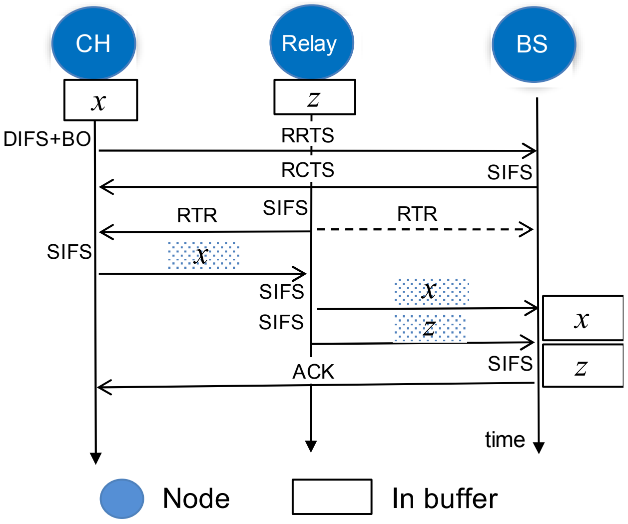
3.3.1 Modified 2-hop path selection protocol with NC (2PSP + NC)

In order for transmissions to be more efficient, modified 2-hop path selection protocol using NC is proposed. Since the transmission from a sensor node to the BS is usually in low speed due to the long distance, the latency is high. Therefore, clustering approach is selected in our work to make the data transfer more efficient and reliable by the NC techniques and multihop approach.

The relay is selected originally in 2PSP focusing on the higher achievable rates by RTR mechanism. The purpose of preferring the higher rate is to accomplish data transmission in low delay and improve the throughput. Our focus is reliability and to achieve the longer network life time. Therefore, the relay selection mechanism prefers a relay node with low energy consumption for forwarding the data message. We modify the original 2PSP in relay selection decision by introducing new rules to the MAC DCF to achieve data transmission through the relay in both high rate and low energy consumption. The energy consumption is estimated using the achievable rates from the RTR mechanism.

Extra data transmission policy with RLNC from relay node to BS is added in the 2PSP procedure of the modified protocol as shown in Figure 5. The 2PSP procedure starts from the beginning of sending a RRTS control message from the CH node until an ACK message returns from the BS. This extra packet is to assist the decoding process at BS. The transmitted packets, x from CH are RLNC-coded packets and the extra transmitted packet from relay will be an innovative information for decoding the RLNC-coded packets if the relay is from the same cluster as the CH. Operation $x \oplus z$ will produce new combination of other packets except the relay's packet and means that RLNC-coded packets are decoded. Therefore, the BS can recover the original messages within fewer transmissions from the CH. For the case of the relay node being from other cluster, the advantages are that the relay node can directly access the medium without competing with other nodes. It can also directly use the higher transmission rate defined by the RTR mechanism of 2PSP protocol. More data packets can be received at the BS with fewer channel access competition and therefore, reduce the delay.

Figure 5 Operation of modified 2PSP protocol (2PSP + NC) (see online version for colours)



3.4 Proposed BCCT/PLNC scheme

BCCT is proposed to solve the problem relating to service denial as we discussed in Section 1.1, where the problem is to satisfy the required packets of all wireless devices in the cooperative group by sharing each other via local wireless connections without needing request to the far BS. The goals of the scheme are to minimise the total number of transmissions and to maintain fairness among the participants in order to save the limited energy resources until all participants satisfy their needs. To maintain fairness, a transmitter is selected for each iteration based on not only the number of packets each member device possesses, usually the one with maximum packets but also the number of transmissions it makes.

The application of physical layer network coding (PLNC) to BCCT is to further reduce the number of transmissions and accomplish the data exchange process quickly. The basic idea of PLNC is to exploit the mixing of signals that occurs naturally when electromagnetic (EM) waves are superimposed on one another (Liew et al., 2013). The simultaneous transmissions by several transmitters result in reception of a weighted sum of signals at a receiver. The advantage is that the number of required time slots can be reduced because transmission from two devices is allowed in the same time slot. Relay is simply an intermediate node that receives addition of combinations transmitted from the devices and broadcasts the coded packet back to the group including the transmitters. In this scheme, relay is one of the other devices in the group.

3.4.1 Algorithm for balanced coding scheme

At the start of data sharing process after receiving packets from the BS, all wireless devices broadcast reception information to announce their packet receiving status. Every node keeps an information table like Table 1. This table describes a sample scenario with four wireless stations in mesh topology shown in Figure 3(e). A station can use this information for deciding a suitable transmitter for next round. For example, stations w_1 and w_3 are missing only one packet each, x_4 and x_5 respectively at initial receiving stage and they possess the maximum number of packets, five out of six. Therefore, the random transmission scheme (El Rouayheb et al., 2010b) selects w_1 and w_3 as transmitters for coded packets with total one transmission from w_1 and two from w_3 to satisfy the requirements of all four stations. As other members are not selected to participate in transmission due to the random scheme, fairness is poor. The purpose of BCCT scheme is to maintain fairness among the participants.

In BCCT/PLNC scheme, one of the stations broadcasts a linear combination of packets in its incoming buffer which are from the set $X = \{x_1, \cdots, x_n\}$ of n packets at each iteration of the algorithm. A coded packet x is denoted by $C_x \in GF(2^n)$, the corresponding vector of linear coefficient, i.e., $x = C_x (x_1, \cdots, x_n)^T$. Y_i is the subspace spanned by vector corresponding to the linear combinations available at station w_i. At the beginning of the algorithm, Y_i is equal to the subspace spanned by vectors that correspond to the packets in $X_i \subseteq X$, i.e., $Y_i = (\{C_x | x \in X_i\})$. The goal of the algorithm is to simultaneously increase the dimension of the subspaces Y_i, $i = 1, \cdots, k$, for as many stations as possible. At each iteration, the algorithm identifies a station $w_i \in W$ whose subspace Y_i is of maximum dimension. If there are more than one station with the maximum number of packets, transmission in BCCT is operated. In BCCT, a station with maximum rank and fewer frequencies of previous transmissions is chosen as transmitter based on the information table. Then, that station wi selects a vector $b \in Y_i$ in a way that will increase the dimension of Y_j for each station $w_j \neq w_i$, and transmits the corresponding packet $b (x_1, \cdots, x_n)^T$.

BCCT/PLNC will apply more transmission with PLNC in earlier stages where only one station has the maximum number of receiving packets. If the packets to be combined do not have the same length, the shorter ones are padded with trailing 0s to make their lengths identical. First, the algorithm chooses a linear combination from a station with maximum number of packets. Then it finds another linear combination from another station that has a rank smaller than the first one. These two combinations are transmitted simultaneously and allowed to add in the air naturally when electromagnetic (EM) waves are superimposed on one another. Relay node deals with the mapping of mixed signal to the desired network-coded signal $S_R = S_1 \oplus S_2$. It broadcasts S_R in second time slot. In the algorithm, two combinations are first added and then transmitted the addition. Short control messages are exchanged for cooperation in the group. In the control message, the time to start transmission is also defined. The second station replies with short control message. Other stations that overhear the message will stop channel access until the transmissions from two stations finish and wait for receiving.

After each round of coded packet transmission, every node performs decoding operation of incoming coded packets and existing received packets. Then the clients update their information table and reception reports are broadcast to decide who should take turn for transmission in next round. At some iteration, the subspaces associated with a number of clients may become identical. This group of clients are merged into a single client with the same subspace.

This procedure is repeated until all clients satisfy their requirements. This is possible due to the fact that all nodes exist within the transmission range and every node can hear the transmission from each other. The significance of PLNC is that the transmitted combinations can carry more innovative information and as a result, more number of client stations can benefit at the earlier iteration of the data exchange process. Therefore, the required transmission time slots can be reduced.

Algorithm 1 Algorithm for BCCT/PLNC scheme

```
Definition: $W$ is set of wireless stations, $X$ is set of received packets, $Y$ is subspace
spanned by vectors corresponding to $X$.
Input: $W$ and $X$.
Output: the maximum value of $Y$ for all wireless stations, $w$.
Begin
for ($i = 1$ to $k$) do{
    $Y_i = <\{C_x | x \in X_i\}>$; //calculate the subspace $Y_i$ for all $k$ wireless stations.
    } //end for loop.
    while (there is a station $i$ with dim $Y_i < n$) do {
    while ($\exists w_i, w_j \in W, i \neq j$, such that $Y_i = Y_j$) do {
        $W = W \setminus \{w_i\}$; //stations with identical subspaces are merged.
    } //end while loop.
    Find stations $w$ with a subspace $Y$ of maximum dimension;
    if (there is only one $w_i$) {
        Find a station $w_j$ with a subspace $Y_j$ of smaller dimension than $Y_i$;
        Select a vector $b_i \in Y_i$ such that $b_i \notin Y_j$ for each $i \neq j$;
        Select a vector $b_j \in Y_j$ such that $b_j \notin Y_i$ for each $j \neq i$;
        Add two vectors, $b = b_i + b_j$;
        Let stations $w_i$ and $w_j$ broadcast packets $x = b.(x_1, \cdots, x_n)^T$;
        Record $w_i$ and $w_j$ as transmitters in information table;
    }
```

```
        else {
            //if more than one station with max dimension, operate in BCCT mode.
            Find a station $w_j$ with a subspace $Y_j$ of maximum dimension that has fewer
            previous transmissions;
            Select a vector $bj \in Y_j$ such that $b_j \notin Y_i$ for each $j \neq i$;
            Let station $w_j$ broadcast packet $x = b\ (x_1, \cdots, x_n)^T$;
            Record $w_j$ as transmitter in information table;
        }
        for ($i$ = 1 to $k$) do {
            $Y_i \leftarrow Y_i + <\{b\}>$; //decoding operation and updating subspace $Y$.
        } //end for loop.
        } //end while loop.
    End
```

Table 1 Example of reception information table: index of received packets and number of transmissions from each wireless station

Wireless stations	*Packets*						*Transmissions*
	x_1	x_2	x_3	x_4	x_5	x_6	
w_1	1	1	1	0	1	1	1
w_2	1	1	0	0	0	1	0
w_3	1	1	1	1	0	1	2
w_4	1	1	0	1	0	1	0

4 Performance evaluation

The performance of proposed framework is evaluated for each specific data transfer mode: data transmission, data collection and data sharing in MATLAB simulation by using performance metrics such as throughput, latency, energy consumption, and fairness. It is also compared to the famous protocol in NC research field, COPE (DCF + NC), the conventional CSMA/CA protocol and 2PSP protocol. Throughput is measured as the amount of payload data that can be received at the destinations for all the unicast data flows transmitted by the sources. Latency is the sum of transmission delay and propagation delay, $M/r + D$ seconds. Where transmission delay is the time to put M-bit message on the channel. M-bit is divided by data rate, r (bits/s). Propagation delay, D, is the time for bits to propagate across the channel and it is calculated by dividing the length of packet in bits by speed of signals, c, which is the speed of light and equals to $3 * 10^8$ m/s. The energy consumption is the energy consumed for the control messages and the successfully transmitted data packets. The energy consumption is defined as the product of power consumed and time spent in transmission over the total amount of transmitted data packets.

The fairness is calculated based on the number of transmissions from each station by the Jain's fairness index (Jain et al., 1984), $\frac{\left(\sum x_i\right)^2}{n\sum x_i^2}$, where *n* is the number of stations participated in the data sharing group and i represents each participant. *x* is the number of transmissions from each station *i*. The value of 1 means the best fairness index.

The transmission rates are calculated based on SINR value obtained from the interference of other nodes' transmissions. The additive interference model as in Iyer et al. (2009) is applied in our simulation. In this model, packet collisions are determined by the cumulative interference and noise instead of using the interference from a single node, one at a time. The SINR perceived by the receiver of link *m*, γ_m is calculated as follow.

$$\gamma m = \frac{P_m \mathcal{A}\left(A_m, B_m\right)}{\sum_{l\in L, l\neq m} P_l \mathcal{A}\left(A_l, B_m\right) + N_m f} \tag{2}$$

P_m is the received power. $A(A_m, B_m)$ is channel attenuation from point A_m to location of the receiver B_m of link *m*. N_m and *f* denote the power spectral density of the thermal noise at the receiver of link *m*, and the frequency bandwidth of the channel, respectively. If SINR value is greater than the SINR threshold corresponding to an acceptable bit error rate (BER), the transmission is successful and the receiver receives the packets. Otherwise, there is a collision. SINR threshold 10 dB and Additive white Gaussian noise (AWGN) are used in our simulation. The power received at the receiver antenna is calculated by the Friis transmission formula in frequency.

$$P_{\mathrm{r}} = P_t G_t G_r \left(\frac{c^2}{(4\pi Rf)^2}\right) \tag{3}$$

This formula relates the free space path loss, antenna gains and wavelength to the received and transmission powers. P_t is the output power of transmitter antenna. G_t and G_r are the gain of the transmitting and receiving antenna with the value 1, respectively. *R* is the distance in meter between the transmitter and receiver. *f* is frequency 5 GHz and *c* is the speed of light.

4.1 Simulation scenarios

As the framework incorporates three schemes, simulation scenarios are different from each other depending on the data transferring modes: data transmission, data collection and data sharing. For the whole framework, the IEEE 802.11a physical and MAC parameters are used to investigate the performance of proposed schemes. The types and values of parameters used in our simulation are shown in Table 2. The size of new XOR header is set 40 bytes as in COPE.

4.1.1 Simulation scenario for necoMAC scheme

For this simulation, two simulation scenarios are generated. In the first scenario, the impact of increasing data flows is investigated. The number of nodes is fixed at 100 and the number of data flows is varied from 10 to 60 flows in the increasing steps of 10 flows. In the second scenario, we focus on the influence of increasing number of nodes on the performance of network. The number of data flows is fixed at 30 flows and the number of nodes is varied from 100 to 600 nodes in increment of 100.

In both scenarios, nodes are uniformly placed over a 1,000 × 1,000 m^2 coverage area. Source and destination node pairs are randomly selected and data flows are created along the paths produced by the AODV routing protocol. The average hop count between source and destination is set 4.5. A data flow denotes a stream of data packets generated at a source node and intended for a particular destination node. All data flows are equal in size (1,500 bytes) and one unicast data packet is transmitted for each pair. The transmissions of data flows are then operated by the proposed scheme and the performance results are measured until the successful reception of all data at the destinations. In each run of simulation, all the nodes, source-destination pairs and corresponding data flows are newly generated.

All the performance metrics used to evaluate in this simulation are calculated for considering the end-to-end values of an entire data flow between source and final destination. The simulation is repeated 50 times and simulation results are averaged of 50 times.

Table 2 Simulation parameters

Parameter	*Value*
Hardware specification	IEEE 802.11a OFDM
Simulation environment	MATLAB 2017a
MAC protocol	CSMA/CA, 2PSP, NCA-CSMA, NCA-2PSP
Transmission power	100 mW
Transmission range	50, 45, 39, 33, 26, 19, 15, 13 m
Transmission rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Antenna type	Omni antenna
RTS, RRTS size	20 bytes
CTS, ACK size	14 bytes
RCTS, RTR size	15 bytes
RTB size	21 bytes
MAC header	34 bytes
XOR header	40 bytes
Slot time	9 μs
Preamble time	16 μs
Signal time	4 μs
SYM time	4 μs
DIFS	34 μs
SIFS	9 μs
Average backoff (BO) time	67.5 μs

4.1.2 Simulation Scenario for necoDG scheme

Simulation for necoDG is performed in two parts. The first part includes clustering the nodes and sending sensor data to the CH. Firstly, nodes are randomly placed by uniform distribution in a 2D 100 × 100 m^2 area and the sink (BS) is placed at the centre of the grid. Clustering the network is performed as described in the first phase of LEACH. We create two clusters in our simulation. Firstly, nodes are organised into clusters and a node is elected as the CH for each cluster based on the probability distribution decision. If a node has been assigned as a CH, it sends advertisements to its neighbours. The neighbour nodes decide which cluster to join based on the signal strength of these messages. After a cluster is decided, data flows from these sources are routed to the CH via the neighbour nodes in multihop fashion. The sensor data packets are sent to the CH and the sink by using the modified 2PSP protocol. The performance is analysed by the increasing number of data flows from 10 to 50 flows with 50 sensor nodes in each cluster. The size of payload data is 1,000 bytes for all data flows.

The second part of simulation is to study the performance of NC and decoding at each CH and at the sink respectively. The CH encodes six incoming data at a time by RLNC. These linear coded packets are transmitted to the sink until the sink can recover all the original data packets. We test the performance of transmission with RLNC compared to the transmission with LEACH.

4.1.3 Simulation scenario for BCCT/PLNC scheme

Fairness and scalability of transmission in BCCT, BCCT/PLNC and the transmission without balanced scheme (El Rouayheb et al., 2010b) (we name as ‘original’) are investigated with respect to the increasing number of packets from 6 to 18 packets and 5 to 21 wireless nodes involved in the cooperative data sharing group. We also analyse the impact of initial packet receiving probability P_{init} on the system performance by using different values 0.3 to 0.9.

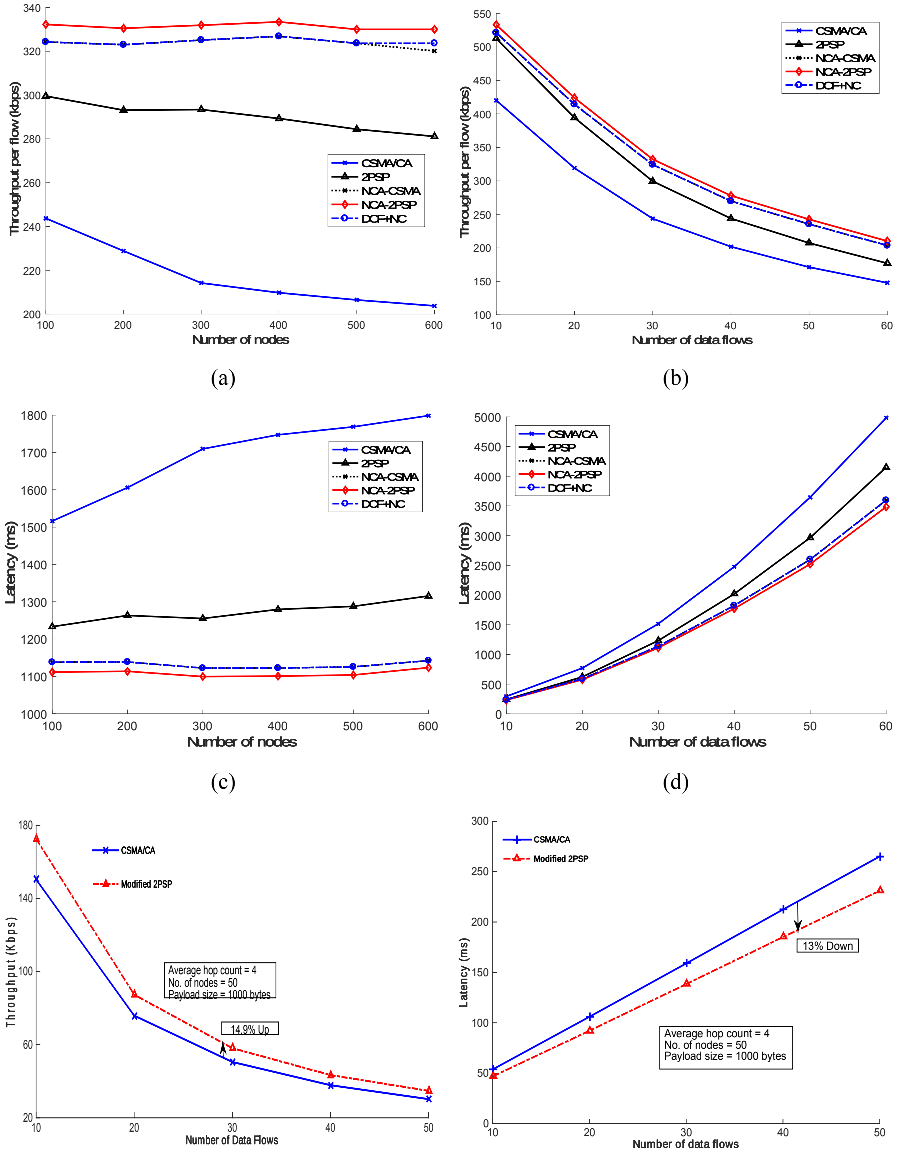
The finite elements from $GF(2)$ are used for indexing and linear NC of each received and lost packet from each station. We also investigate the difference in the number of time slots required by the BCCT/PLNC scheme to see how PLNC can help the data sharing process accomplish earlier than the one without PLNC. We assume that the synchronisation problem for the transmission of two coded packets is solved by other mechanism. The results are the averaged values over the 50 experiments.

4.2 Simulation results and discussions

4.2.1 Throughput and latency of necoMAC and necoDG schemes

Figure 6(a) and Figure 6(b) show the results of network throughput versus the number of nodes and data flows for the proposed protocols in necoMAC scheme. The proposed scheme shows high throughput than the CSMA/CA and 2PSP protocol for all nodes numbers and for all flows number. The throughput improvement is approximately 51.51% in average in the first case and 28% in the second case.

Figure 6 Throughput and latency of necoMAC and necoDG schemes (see online version for colours)



(a) (b)

(c) (d)

(e) (f)

Notes: (a) Throughput as a function of nodes increase, (b) Throughput as a function of flows increase, (c) Latency as a function of nodes increase, (d) Latency as a function of flows increase and (e) Throughput as a function of flows increase and (f) Latency as a function of flows increase

The throughput values are for the fixed amount of data for each data flow. For total 30 data flows, the amount of data from 30 sources is 360 kb and NCA-2PSP protocol can achieve 330 kbps for one data flow. This means that throughput of the network with 30 data flows becomes 1 Mbps for transferring 360 kb data from 30 sources. With this rate, all data from the sources can be received within 400 ms. However, the latency for the same value is over 1,100 ms in Figure 6(c). This is because latency includes not only the actual transmission time but also the delay for the medium access. This fact becomes clear when the number of data flows increases in the network with 100 nodes in Figure 6(b). Throughput decreases and latency gets higher with increasing number of data flows Figure 6(d). High latency means low throughput. When the number of flows in the network increases, there is high possibility of contending the channel access by many nodes for sending the data, which leads to the delay and affects throughput performance. It can be seen that proposed NCA-2PSP protocol takes the lowest latency compared to other protocols, with 34.66% and 29.84% reduction in Figure 6(c) and Figure 6(d) respectively than CSMA/CA protocol. This shows that NCA-2PSP protocol can find more relay nodes that helps the transmissions in high rate and leads to throughput improvement when the number of nodes increases. NC and relaying in high rate lead to less number of transmissions and less total transmission time. We provide the detail results of average throughput, latency and energy consumption values in Table 3.

Figure 6(e) and Figure 6(f) show the results of network throughput and latency versus the number of traffic flows for the modified 2PSP protocol in necoDG scheme. The modified 2PSP protocol outperforms CSMA/CA protocol by up to 14.9% in average. Throughput decreases as the number of data flows increases like in the case for necoMAC scheme. The reason for this behaviour is because of the high latency when data flows increase. When the number of flows in the network increases, there is high possibility of competing the media access, which leads to the delay and affects the throughput performance. However, the advantage of the modified 2PSP protocol is that it can transmit in high rates with the help of relay node without waiting for the NC opportunity from counter-directional data flows. Furthermore, an extra packet transmitted from the relay is helpful for the decoding operation and transmission process can be accomplished earlier than the legacy system like CSMA/CA. The latency of modified 2PSP is 13% reduced compared to that of CSMA/CA.

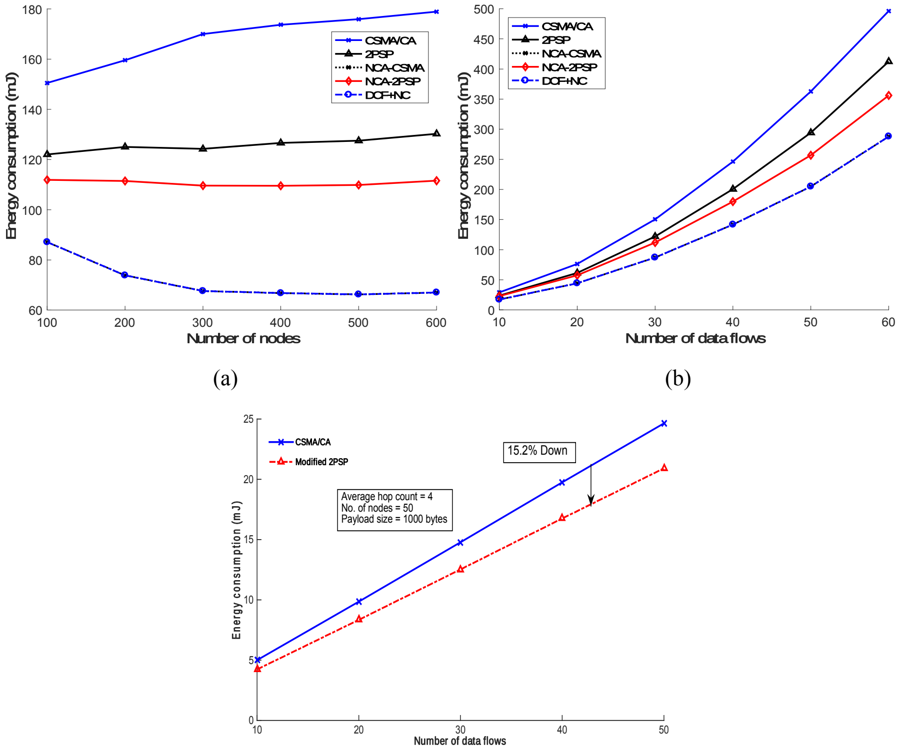
Table 3 Comparison Results for necoMAC for increasing number of data flows

	Throughput (kbps)	*Latency (ms)*	*Energy consumption (mJ)*
NCA – 2PSP	336.70	1616.2	164.22
DCF + NC	328.09	1663.9	130.55
2PSP	305.78	1873.1	185.79
CSMA/CA	250.65	2281.6	226.88

4.2.2 Energy consumption of necoMAC and necoDG schemes

Figure 7(a) and Figure 7(b) show that NCA-2PSP consumes less energy than CSMA/CA and 2PSP protocols but more energy than COPE. The energy consumption is defined as the product of consumed power and time spent in transmission over the total amount of transmitted data packets. For example, energy consumption for one transmission in CSMA/CA is *Transmission Power* $*$ ($T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK}$). The total energy consumption increases as the number of data flows increases, but not much difference with the increase in the number of nodes inside the network. The amount of energy saving is, in average, about 28.15% for the case of increasing flows while it is about 34.43% when the number of nodes increases up to 600. The reasons for these results are that increasing number of nodes with the fixed number of 30 flows does not affect the energy consumption of the protocol much. Nodes are active only when data flows pass through them. Therefore, energy consumption increases significantly when the number of data flows increases in Figure 7(b).

Figure 7 Energy consumption of necoMAC and necoDG schemes, (a) energy consumption as a function of nodes increase, (b) energy consumption as a function of flows increase and (c) energy consumption of modified 2PSP (see online version for colours)



(a) (b)

(c)

This is also true for the modified 2PSP protocol of necoDG scheme where sensor data are transmitted from 50 source nodes to the CH. As Figure 7(c) depicts, the total energy consumption increases proportionally as the number of data flows from the clusters increases. In necoDG scheme, each CH node encodes 6 data packets from its own cluster together each time it transmits to the sink. Transmission with RLNC coding scheme needed 25 transmissions with link quality probability equal to 0.5 and costs 5.2 μJ for successful receiving of 6 original data packets. The amount of energy consumption by the modified 2PSP protocol for 10 data flows is 4.2302 mJ and 20.913 mJ for 50 flows. The amount of energy saving due to the modified 2PSP protocol is about 15.2% in average. For the total 50 data flows from a cluster, the energy consumption is 0.26 mJ from the CH to the sink and 20.913 mJ from sensor nodes to the CH. It means that it will totally cost 42.346 mJ for all the 100 data flows from the sensor nodes in two clusters while the energy for 100 transmissions from sensor nodes to the sink by LEACH is 500 mJ.

Discussion

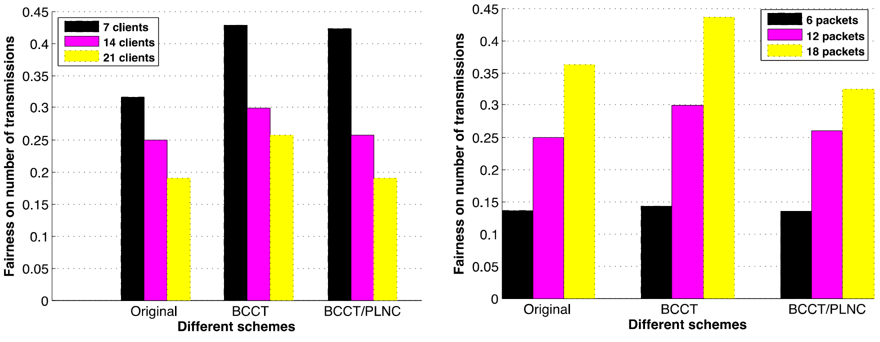
The necoMAC scheme incorporates NCA-CSMA, NCA-2PSP, 2PSP and CSMA/CA protocols. We design the NC-aware CSMA to apply for a three-node golden chain and NC-aware 2PSP that works for a golden triangle with multirate transmission capability. The simulation results reveal that more than 20% of energy consumption is saved and 20–50% of throughput is improved by the proposed protocols. In necoDG scheme, RLNC technique is applied at the CH for the coded data transmission to the sink for improving reliability and decreasing retransmissions. We propose a modified 2PSP protocol by appending an extra packet transmission opportunity to the relay node to accomplish the data transmissions from sensor nodes to the sink quickly. The simulation results show that the modified 2PSP can reduce the energy consumption up to 15.2%.

4.2.3 Results of BCCT/PLNC scheme

4.2.3.1 Fairness of the number of transmissions

In this section, the fairness of the three schemes are discussed with respect to the increase in the number of packets and wireless stations. The fairness is calculated based on the number of transmissions from each station by the Jain's fairness index. From Figure 8(a), it is clear that fairness decreases with the increase in the number of client devices for all three schemes with total 12 packets requirement. This is because when the number of client devices increases, there is less chance to participate from most clients. This is also depending on the number of packets received initially. After many iterations of transmission from the stations with higher number of packets, all stations satisfy their needs and no chance of transmission from other stations.

Figure 8 Fairness of three schemes with varying number of packets and client devices, (a) comparison of different schemes with 12 packets (b) comparison of different schemes with 14 client devices (see online version for colours)



(a)

(b)

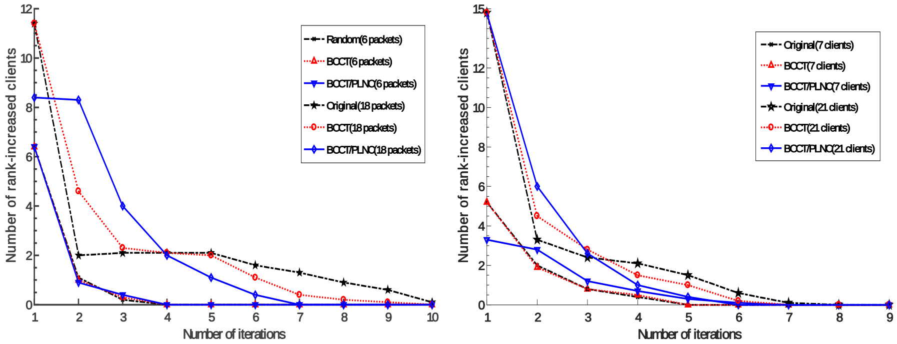
Reversely, fairness value increases with the increasing number of packets for all schemes in Figure 8(b). If the required number of packets is high for many stations, the more iteration of transmissions is needed. Therefore, the chance to become a transmitter is higher for most of the stations in the group. This makes the average fairness of transmissions from each station high.

For both cases, BCCT is the best among the three schemes. The fairness of the BCCT/PLNC is not as good as that of BCCT. This is because the main purpose of BCCT/PLNC scheme is to reduce the required time slot and number of transmissions. The selection of transmitters is based on the higher priority given to improve the coding operation. At the later iteration, the random node participates in forwarding the coded packets. From the standpoint of client station, they still need to involve in the simultaneous transmission until the algorithm notices the redundant transmissions. The effect of PLNC over BCCT is depicted in Figure 9.

4.2.3.2 Effect of PLNC over BCCT

In BCCT/PLNC, addition of two coded packets are transmitted at the same time. It can help more stations to benefit from the coded packet and reduce their requirements earlier than BCCT and the random scheme. Figure 9 shows the number of stations that gradually received the required packets at each iteration of data transmission. Figure 9(a) depicts the changes due to the increase in required packets (from 6 packets to 18 packets) and Figure 9(b) shows the changes due to the increase in the number of stations (from 7 clients to 21 clients).

Figure 9 The number of clients that increased their ranks in each iteration of the data sharing process with respect to, (a) different number of packets with 14 clients (b) different number of clients with 12 packets (see online version for colours)



(a) (b)

In earlier iterations, transmission occurs in PLNC where many client devices can recover their lost packets from the PLNC-coded packets. At time slot 1, the number of benefited receivers is high because the transmitted combination is innovative. As the requirements of clients are fulfilled from iteration to iteration, the graph gradually declines in later iterations. The lines of BCCT and original scheme are especially high in the middle of the process. This means that the PLNC transmission scheme increases the rank of the subspace of many receivers simultaneously at earlier iterations. This helps the data exchange process to accomplish quickly and also ensure that all the devices in the cooperative group recover their lost packets. Therefore, bandwidth and energy resources are saved.

4.2.3.3 Comparison of total number of transmissions

The scalability of the system is tested with the number of packets and client stations. The algorithms for both BCCT and BCCT/PLNC schemes show a good performance result which lies closer to the lower bound on the required number of transmissions as defined in the reference paper (El Rouayheb et al., 2010b) and more than 50% less than the trivial bound. The BCCT/PLNC scheme requires fewer numbers of transmissions than the BCCT as depicted in Figure 10.

In Figure 11, the impact of initial packet receiving probability P_{init} to the total number of required transmissions is depicted. The results are for three values of P_{init} with 0.3, 0.5 and 0.6. With $P_{init} = 0.3$, the number of initial receiving packets is low and more number of transmissions are needed than that of $P_{init} = 0.5$ and $P_{init} = 0.6$. This means that initial packet receiving probability has a high impact on the number of transmissions and the fairness.

Figure 10 Performance of the algorithms for the increasing number of packets with 5 client devices (see online version for colours)

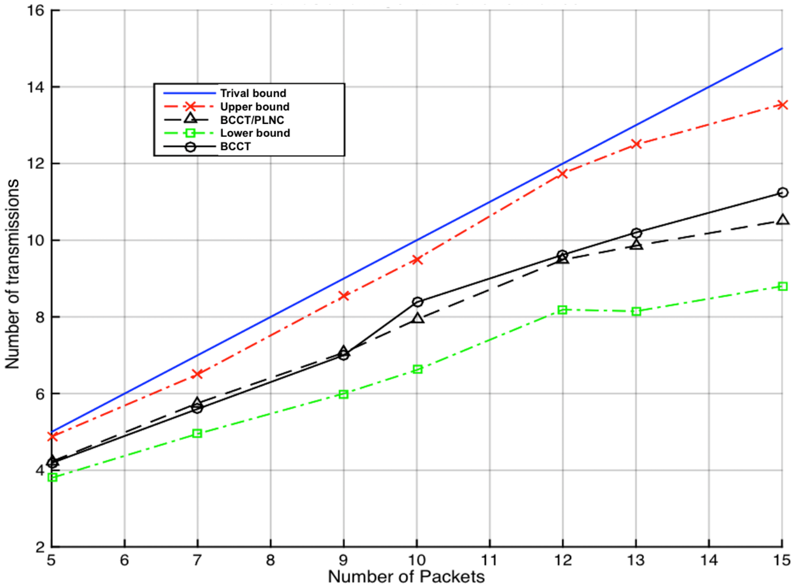
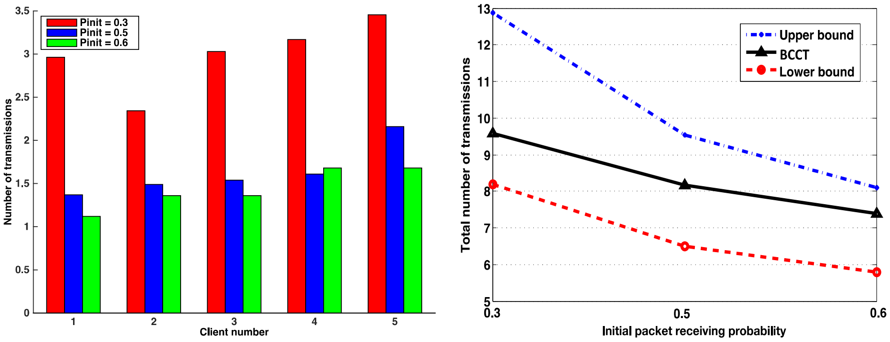


Figure 11 Impact of initial packet receiving probability P_{init} for 5 client devices and 10 packets, (a) transmission from each client and (b) total number of transmissions (see online version for colours)



(a) (b)

Discussion

We propose a balanced linear coding scheme and a transmission scheme with physical layer NC for the data exchange problem to maintain the fairness among the client devices and to accomplish the process with minimum number of transmissions. Our schemes create an information table that keeps the packet reception information and the number of transmissions each client makes in each round of data exchange process. This knowledge is important for deciding the next transmitter to maintain fairness among the clients to ensure that a certain client does not run out of energy and leave the group. With our schemes, the total number of transmissions decreases while distributing the work load among the clients. Moreover, by allowing two clients to simultaneously transmit their linear combinations by the physical layer NC, our simulation results show that clients receive their required packets mostly in the earlier iteration of the process. As a result, it satisfies the requirement of participants as quickly as possible and leads to the quick completion of data exchange process. The number of transmissions is within the lower and upper bounds and the algorithms maintain scalability for the case of increasing number of packets.

5 Conclusions

This paper presents a new data communication framework for the predominant paradigms of future wireless communication such as 5G and IoT applications. For this framework, we develop medium access control protocols for data transmission, data collection and data sharing schemes by utilising topology and NC techniques. We design a network coding-aware medium access control (necoMAC) scheme to achieve higher throughput with low energy consumption. The protocols in this scheme utilise chain and triangle topologies as the golden resources for the NC opportunity. The topology management mechanism is incorporated in MAC protocols. We propose an energy-efficient NC-based data gathering scheme called necoDG. An average 15.2% of energy saving and 13% reduction in latency is achieved. We also introduce a balanced cooperative network coded transmission scheme called BCCT, which is developed by using linear coding and physical layer NC techniques. This scheme can achieve fairness improvement among devices and also reduce the number of transmissions. Therefore, energy and bandwidth could be saved and network lifetime increases. The framework can provide data transferring services such as data transmission, data collection and data sharing at a single layer in more efficient way in terms of high throughput, low latency, fairness and low energy consumption. The overall performance of the network is improved due to the proposed schemes. This framework is a first step for combination of different scenarios of future wireless networks and could be added more functions for the new applications to improve the performance of the network. Based on the results and observation in this study, we can conclude that NC can be applied effectively by incorporating into the existing technologies or by developing algorithms and efficient code construction for various new scenarios to tackle the challenges of future wireless networks.

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