Data Synchronization for Throughput Maximization in Distributed Transmit Beamforming

Alireza Ghasempour and Sudharman K. Jayaweera

Communications and Information Sciences Lab (CISL),
Department of Electrical and Computer Engineering,
University of New Mexico, Albuquerque, NM
and
Bluecom Systems and Consulting LLC, Albuquerque, NM

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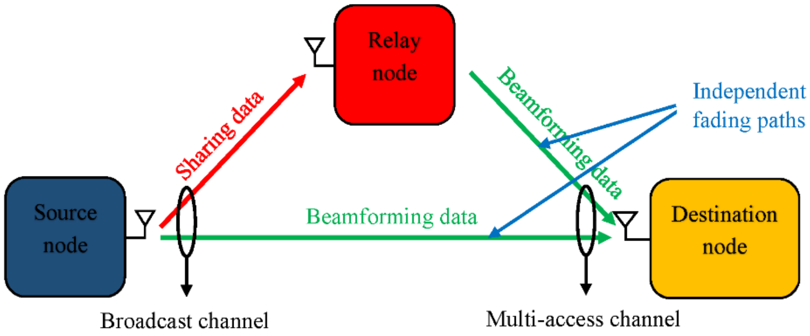
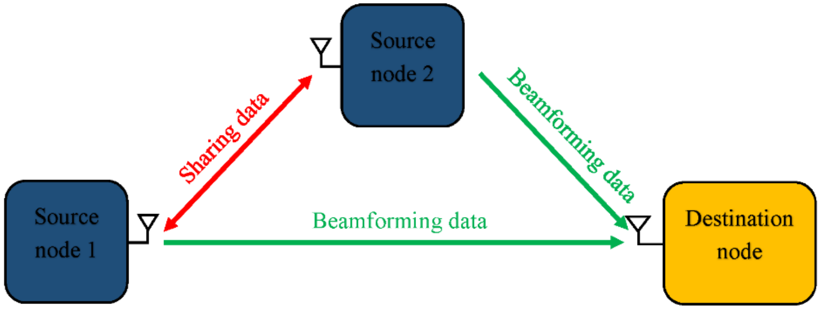
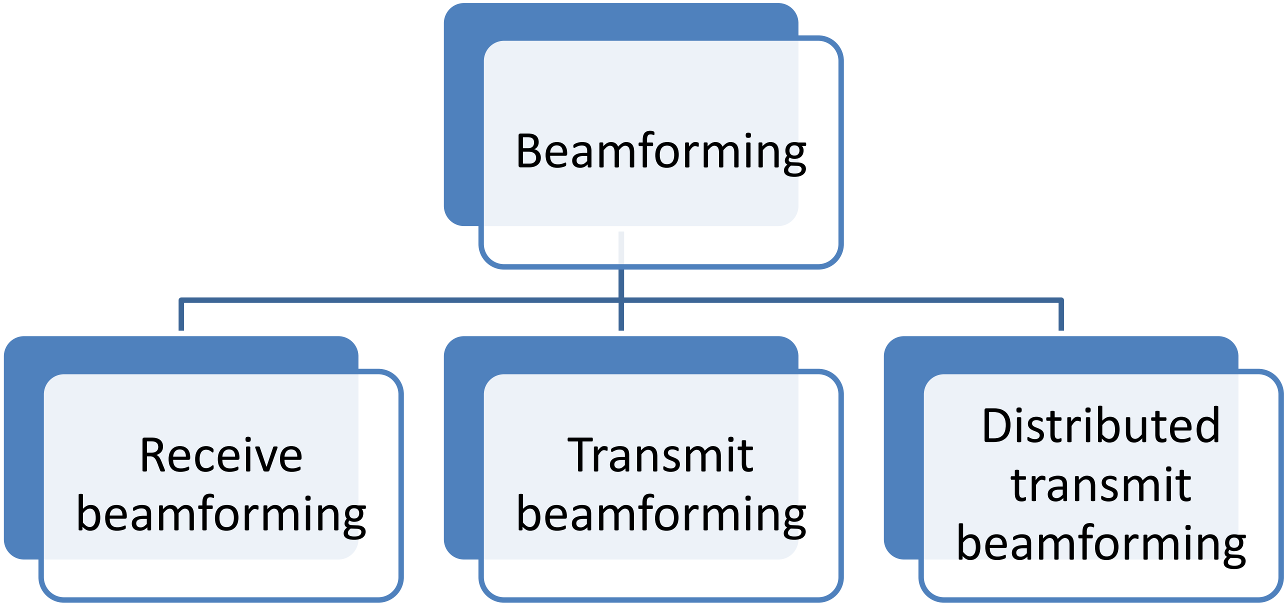
Cooperative wireless communication

- In cooperative wireless communication, we have a wireless network of source nodes want to enhance their effective quality of service via cooperation.
- Each node is assumed to be a source node as well as a cooperative node for other source nodes.





Beamforming



Beamforming

Receive beamforming

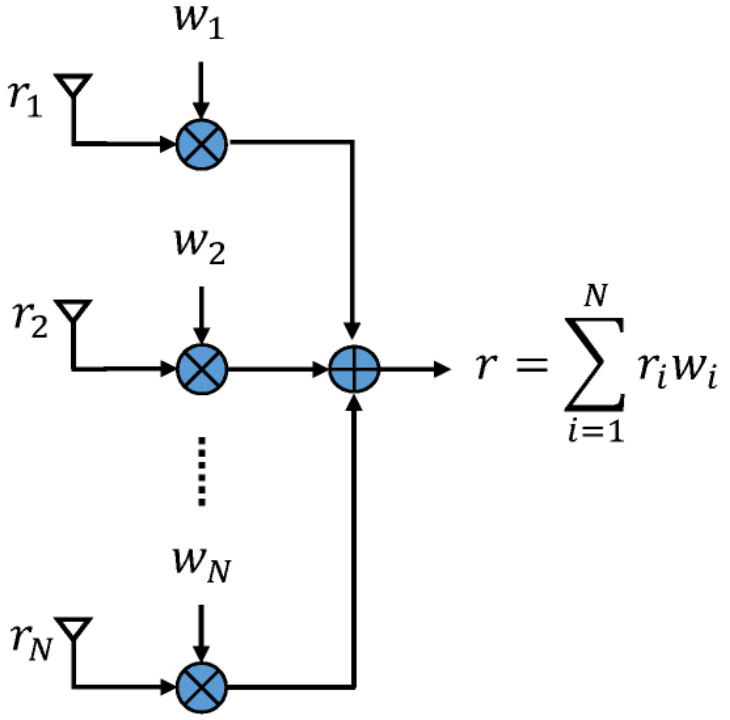
Transmit beamforming

Distributed transmit beamforming

Receive beamforming

- The destination node (receiver) has N antennas to receive replicas of the same transmitted data.
- The output of each antenna is multiplied by a complex-valued beamforming weight and then linearly combined.

r_i: received signal at i-th antenna
w_i: i-th beamforming weight
r: the output of the combiner



$$r = \sum_{i=1}^{N} r_i w_i$$

Combining schemes

- **Selection Combining (SC)**

The received signal from the antenna with the largest instantaneous SNR is passed to the output of combiner. Only one of the beamforming weights is non-zero.

- **Equal-Gain Combining (EGC)**

Amplitude of beamforming weights are all equal and only their phases are matched to the phase of the corresponding channel. Outputs of multipliers have zero phase shift and add up coherently.

- **Maximal-Ratio Combining (MRC)**

The received signals are weighted according to noise power and channel gain at each antenna and then combined constructively.

Transmit beamforming

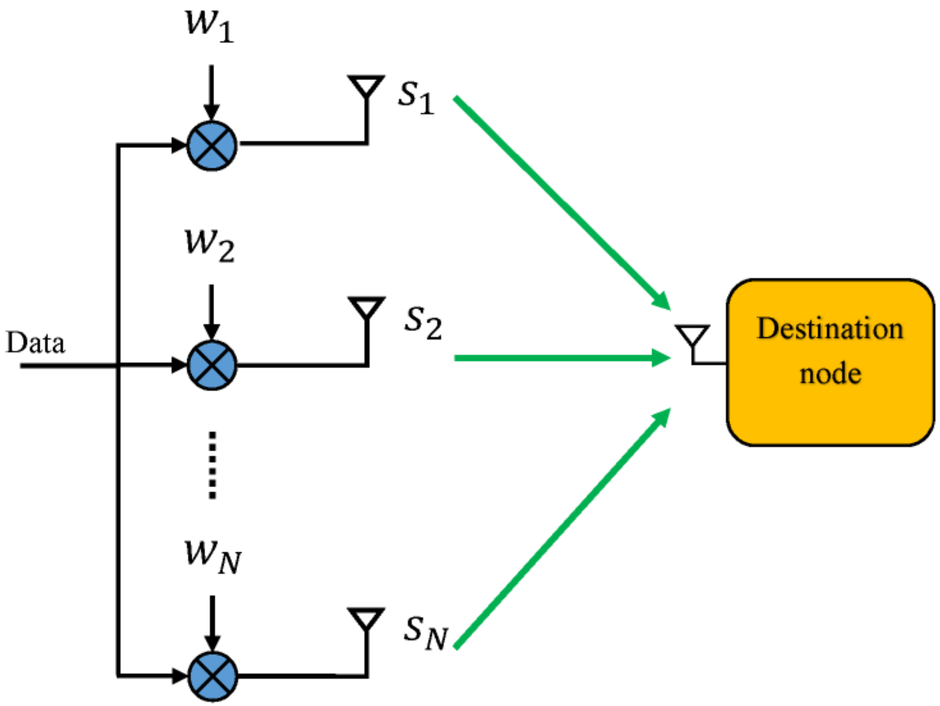
- When the channel state information at the transmitter is known, transmit beamforming can be used to achieve diversity gain as well as array gain at the receiver.
- Array gain is the increase of average SNR at the receiver by coherent combining of signals at multiple antennas at the receiver or transmitter or both.
- Diversity gain is the increase in signal-to-interference ratio by compensating for channel fading by using space diversity.

Transmit beamforming

The transmitter has N antennas and multiplies the data of each antenna by corresponding beamforming weights so that the received signals at the destination node are combined constructively.

s_i: signal transmitted from the i-th antenna

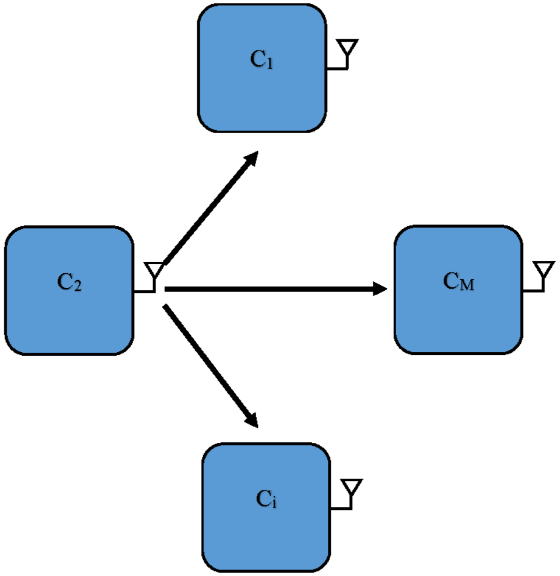
w_i: i-th beamforming weight

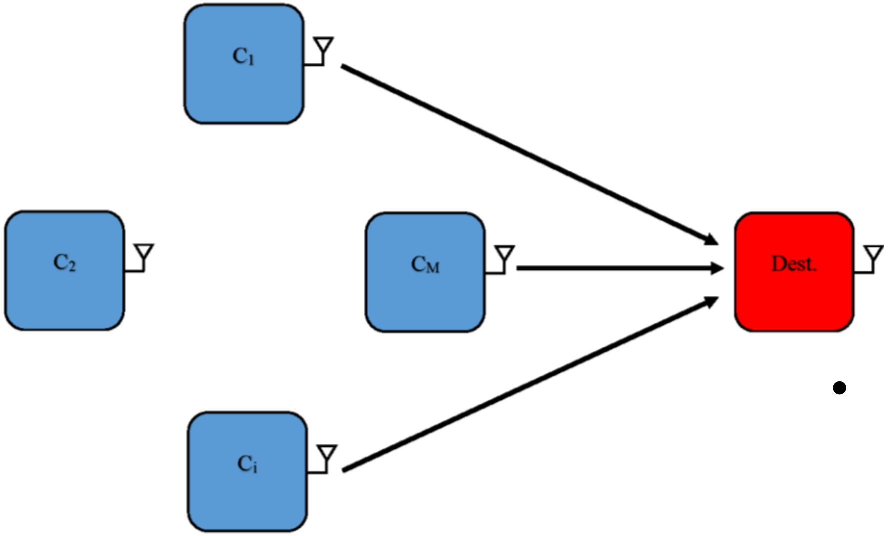


Distributed transmit beamforming

Distributed transmit beamforming is a cooperative communications technique in which two, or more, spatially separated nodes act as elements of an antenna array to beamform common data to a destination node.

- **Data sharing:** During this step, cooperative nodes share their data with others to achieve data synchronization.





- **Beamforming:** During this step, cooperative nodes transmit the shared data to the destination node using proper beamforming weights.

Distributed transmit beamforming Benefits

- Distributed transmit beamforming, can be used to achieve:
  - Increased data rate
  - Reduced power scattering in unwanted directions
  - Reduced interference
  - Increased security
- If there is an M number of cooperative nodes for distributed transmit beamforming, this can provide:
  - M-fold increase in the received signal amplitude
  - M^2-fold increase in the received power
  - M -fold increase in the signal-to-noise ratio
  - M -fold increase in the transmission range for free space propagation
  - M -fold decrease in the transmitted power (for a fixed received power)
  - M -fold increase in the energy efficiency gain

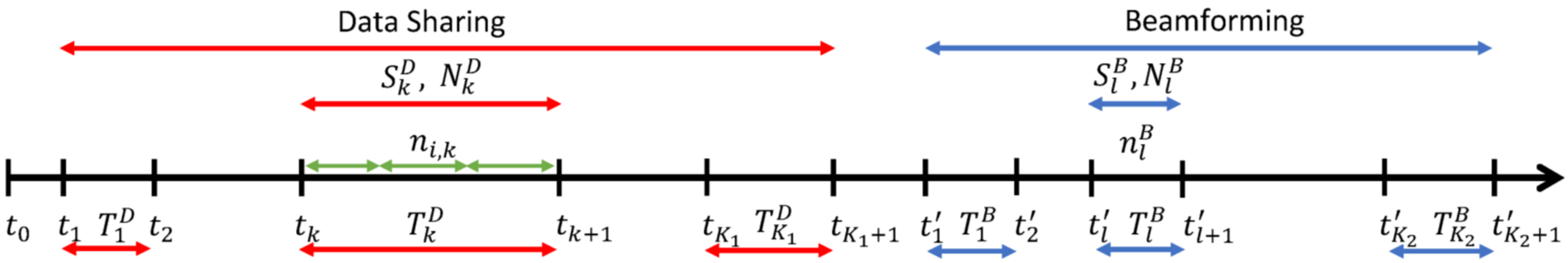
Distributed transmit beamforming: Key challenges

- Distributed data synchronization
- Distributed timing synchronization among cooperative nodes
- Distributed carrier frequency synchronization
- Distributed carrier phase synchronization

Data Sharing

Objective: find the optimum number of packets that each cooperative node should send to others during each data sharing time interval so that the total throughput during the distributed transmit beamforming stage is maximized.

Timing scenario for data sharing and beamforming



T_k^D: The k-th data sharing time interval

T_l^B: The l-th beamforming time interval

S_k^D: Indices of cooperative nodes during T_k^D

S_l^B: Indices of cooperative nodes during T_l^B

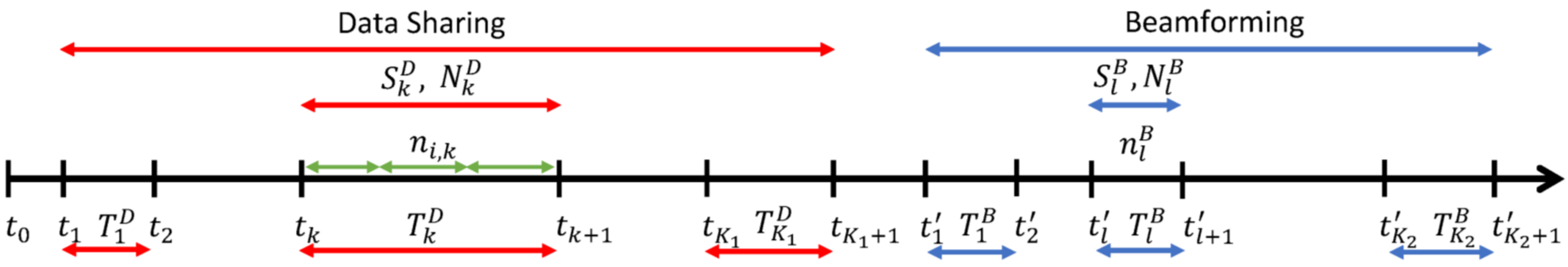
N_k^D: The total number of packets that the cooperative nodes can share during T_k^D

$n_{i,k}$: The number of packets that cooperative node i sends to others during T_k^D

n_l^B: The number of transmitted packets to the destination node during T_l^B

N_l^B: The maximum number of packets that cooperative nodes can send during T_l^B

Optimization problem formulation



$$\text{Maximize} \sum_{l=1}^{K_2} n_l^B \tag{1}$$

$$n_l^B = min\left(N_l^B, n_l^c\right), l = 1, \dots, K_2, \tag{2}$$

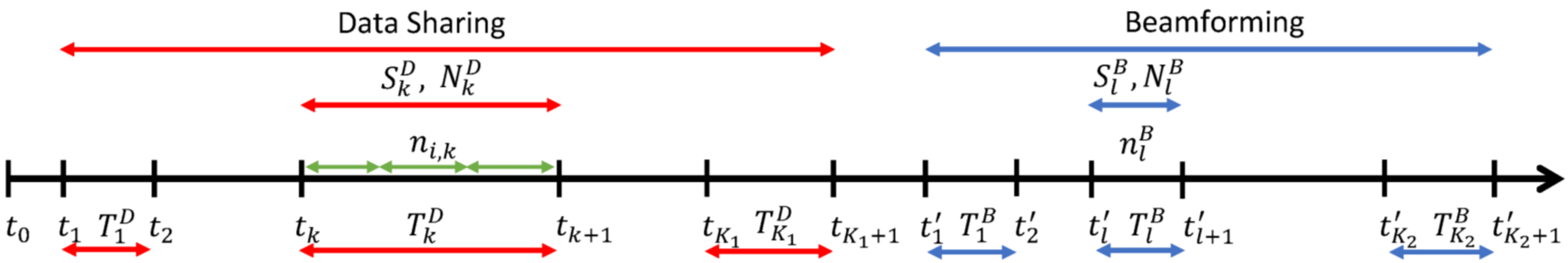
$$n_l^c = \sum_{i \in S_l^B} \min_{j \in S_l^B} n_{i,j,l}^S, l = 1, \dots, K_2 \tag{3}$$

$$n_{i,j,l}^S = \begin{cases} n_{i \to j} & if\ l = 1 \\ n_{i,j,l-1}^S - n_{l-1}^B & if\ l = 2, \dots, K_2 \end{cases} \tag{4}$$

$$n_{i \to j} = \sum_{k=1}^{K_1} n_{i,k} I_k(j) \tag{5}$$

$$0 \leq n_{i,k} \leq N_k^D,\ \sum_{i \in S_k^D} n_{i,k} = N_k^D,\ k = 1, \dots, K_1 \tag{6}$$

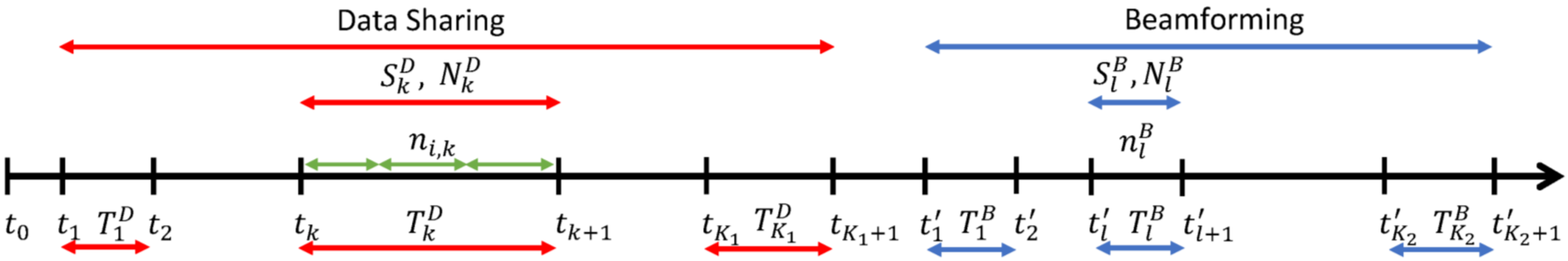
Solution methods



The optimization problem (1)- (6) is a nonlinear optimization problem for which there is no apparent direct closed-form solution.

- **Exhaustive search**
- **Heuristic methods**

Exhaustive search



The exhaustive search can be implemented by checking, for $k = 1, \dots, K_1$, all possible integer values of $n_{i,k}$ from 0 to N_k^D subject to $\sum_i n_{i,k} = N_k^D$ and finding their optimum values so that (1) would be maximized.

Example: if $S_k^D = \{1,2\}$ and $N_k^D = 5$, then for $n_{1,k}$ and $n_{2,k}$ we must check all possible integer values from 0 to 5 such that $n_{1,k} + n_{2,k} = 5$.

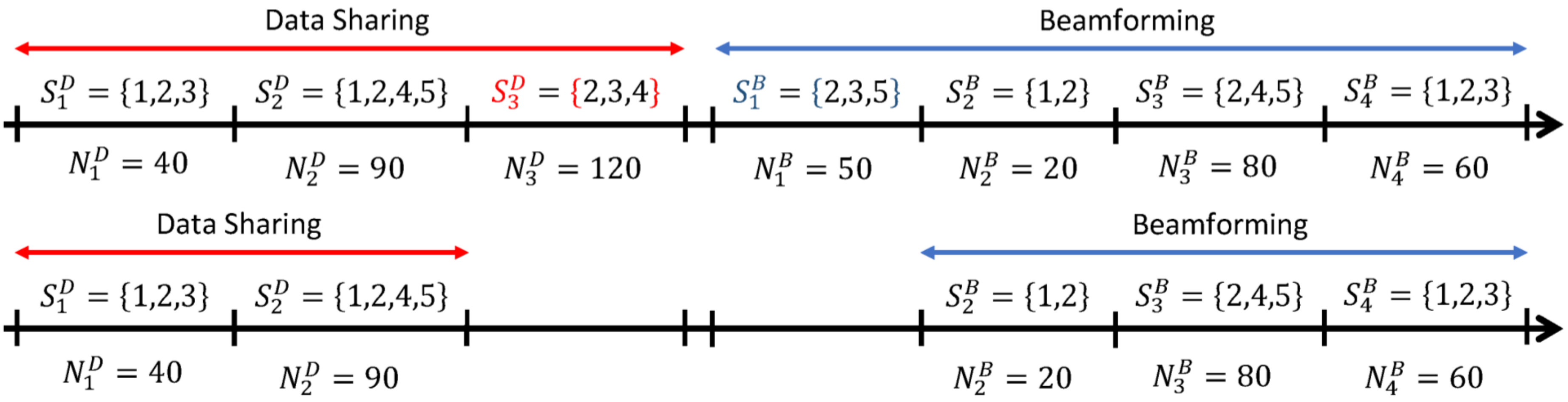
In this case, the possible values of $n_{1,k}$ and $n_{2,k}$ are (0,5), (1,4), (2,3), (3,2), (4,1), and (5,0).

In general, using exhaustive search to find the optimum solution may not be desirable due to its very high computational complexity.

A novel heuristic method

In our proposed heuristic method, first, we first use the following two steps to remove those unnecessary sets S_k^D, S_l^B which will not influence the problem optimization:

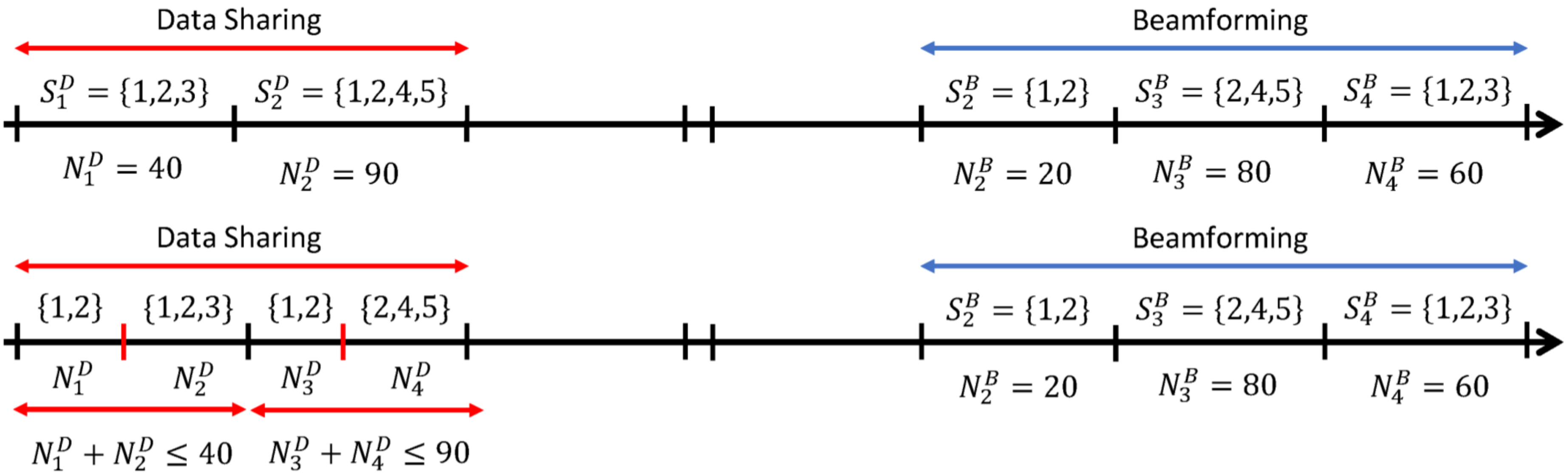
1. Drop any S_l^B which is not the subset of any set or sets in the data sharing time intervals, e.g., $S_1^B \notin S_k^D, k = 1,2,3$.
2. Drop any S_k^D none of whose subsets is a given set in the beamforming stage, e.g., $\mathrm{S}_l^{\mathrm{B}} \notin S_3^D, l = 1,2,3,4$.



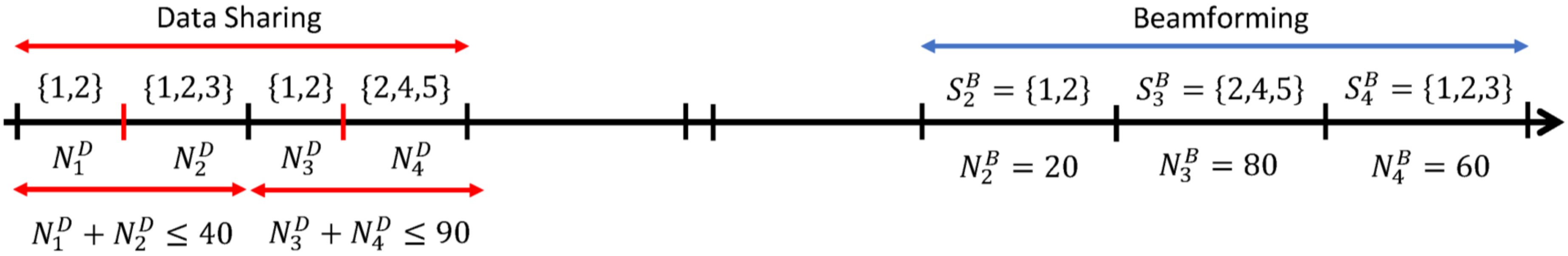
A novel heuristic method: Step 1

After removing the redundant sets, the data sharing optimization can be performed in two steps:

1. For $k = 1, \ldots, K_1$: In each T_k^D, select a subset/s of cooperative nodes from S_k^D based on S_l^B and N_l^B. Divide each time interval T_k^D to several disjoint subintervals based on the number of such elected subsets.



A novel heuristic method: Step 1



- The values of N_1^D and N_2^D (and similarly for N_3^D and N_4^D) have to satisfy the following constraints:

$$N_1^D + N_2^D \leq 40$$
$$N_1^D \leq N_2^B$$
$$N_2^D \leq N_4^B$$

- Additionally, we impose the following fairness criterion:

$$\frac{N_1^D}{N_2^D} = \frac{N_2^B}{N_4^B}$$

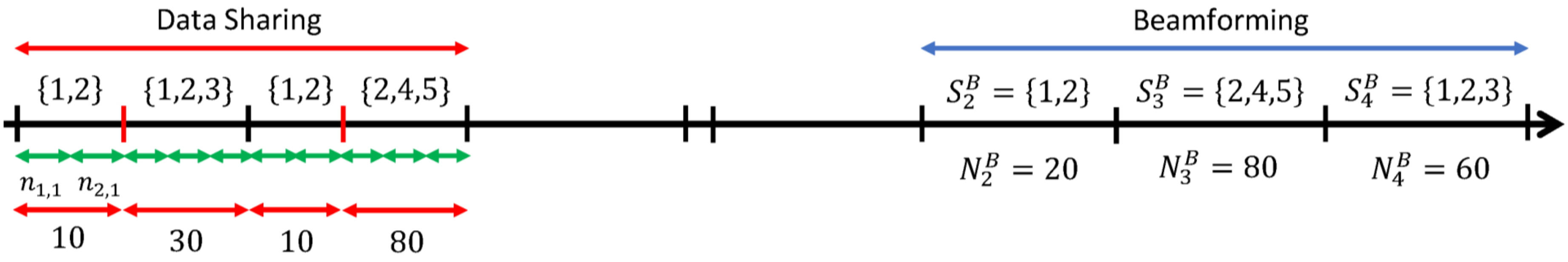
Result: $N_1^D = 10, N_2^D = 30, N_3^D = 10, N_4^D = 80.$

A novel heuristic method: Step 2

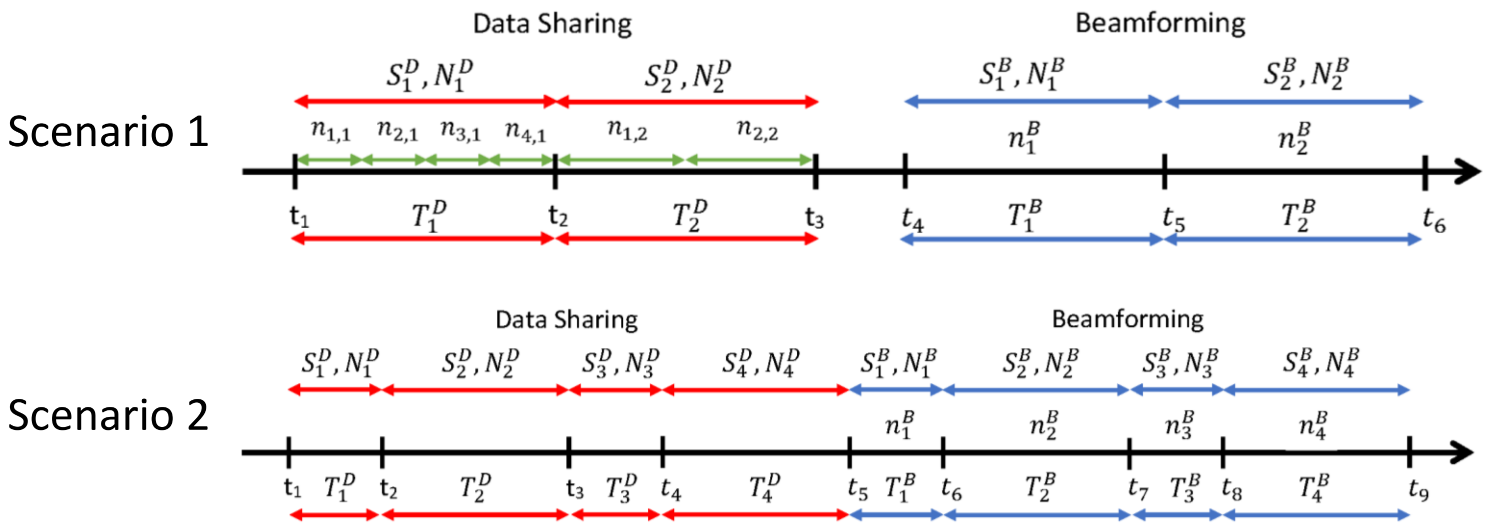
2. The optimum values of $n_{i,k}$ are computed based on S_k^D, $N_{i,k}$, and N_k^D such that a fairness criterion over cooperative nodes is maintained (i.e., the number of transmitted packets by source nodes should be proportional to their available data). We assume that all cooperative nodes consume the same energy per packet E_p and they have enough packets to share in each data sharing time interval, it turns out that

$$\frac{n_{i,k}}{N_k^D} = \frac{N_{i,k}}{\sum_{i \in S_k^D} N_{i,k}}$$

$N_{i,k}$: The number of packets that node i has at the beginning of the k-th data sharing time interval T_k^D where $N_{i,k} \geq N_k^D$.



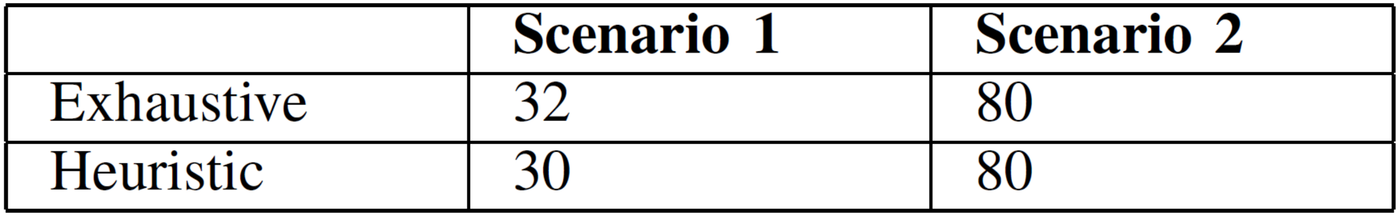
Numerical examples



Parameter	**Value of scenario 1**	**Value of scenario 2**
M	4	3
K_1, K_2	2, 2	4, 4
N_1^D, N_2^D	22, 10 Packets	10, 20 Packets
N_3^D, N_4^D	N/A, N/A	20, 40 Packets
S_1^D, S_2^D	$\{1,2,3,4\}, \{1,2\}$	$\{1,2\}, \{1,3\}$
S_3^D, S_4^D	N/A, N/A	$\{2,3\}, \{1,2,3\}$
N_1^B, N_2^B	10, 100 Packets	10, 30 Packets
N_3^B, N_4^B	N/A, N/A	10, 30 Packets
S_1^B, S_2^B	$\{1,2\}, \{3,4\}$	$\{1,2\}, \{1,3\}$
S_3^B, S_4^B	N/A, N/A	$\{2,3\}, \{1,2,3\}$

Simulation results

The total number of transmitted packets in two scenarios by the exhaustive search and the proposed heuristic method.



	Scenario 1	**Scenario 2**
Exhaustive	32	80
Heuristic	30	80

Conclusion

- Distributed/cooperative transmit beamforming can be implemented in two steps:
  - Data sharing
  - Distributed beamforming
- The goal of data synchronization among cooperative nodes is to maximize the transmitted data throughput during distributed transmit beamforming.
- This was formulated as an optimization problem and we proposed a low-complexity heuristic method to solve it.
- Numerical examples showed that the proposed heuristic method can provide excellent performance compared to the exhaustive search at a very low computational complexity.

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Thank you

Any questions