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A Mathematical Model for Cross Layer Protocol Optimizing Performance of Software-Defined Radios in Tactical Networks

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ABSTRACT Unlike conventional mobile ad hoc networks, tactical networks, which provide communication of software-defined radios (SDRs) in mission critical and time-sensitive applications, require cognitive functions across the TCP/IP stack to encounter strict constraints while providing smooth incorporation with IP-based applications. The tactical applications are mission-critical and thus pose unique requirements for the network, including decentralized control and mission specific latency bounds for end-to-end data delivery. This paper presents a mathematical model for a cross-layer design, which optimizes trade-offs among different configurations of the SDRs to achieve maximum performance in terms of energy efficiency, reliable packet delivery at an appropriate data rate and within affordable latency bounds in multi-hop tactical networks. The proposed model is used in a number of mission-critical network scenarios to demonstrate enhanced performance, where SDRs effectively adapt to the dynamic environment.

INDEX TERMS Tactical networks, cross layer designs, multi-hop solutions, optimization parameters.

I. INTRODUCTION

Mission critical networks such as tactical networks and disaster recovery networks present a challenging environment for communication. A tactical network must support dynamically changing operational priorities, where bandwidth is scarce [1]. In time and mission critical applications, tactical MANETs perform a vital role because of their specialty of designing a network on demand and in scenarios where deployment of physical infrastructure-based network is impossible. Other than military-based applications, disaster scenarios such as floods, earthquakes, hurricanes etc. require a network that is quickly deployed. Such networks must take control in scenarios of communication in absence of an infrastructure to handle critical challenges tactfully. Hence there is a need to design an efficient framework that provides flexibility and reliability during transmission of highly sensitive and critical military information in defense networks [2].

Tactical network needs to be highly mobile as well as continuously operational in unfavorable conditions such as destroyed/unavailable nodes or congested or down links [3]. Therefore a static infrastructure does not fulfill the communication requirements of such networks. Moreover, there may also be situations such as military operations or calamities when the infrastructure itself is destroyed or absent.

Therefore, the communication in tactical networks is a two-fold challenge. First, the communication must happen in an efficient manner even when the resources such as bandwidth, power and time are scarce. Second, quality of service must be ensured even in the presence of constraints such as channel impairment, noisy channel and poor signal-to-noise ratio. Due to these specific challenges, tactical based systems need to have a communication mechanism that is reliable, robust as well as secure [4]. In context of functional patterns, all tactical networks share similar characteristics that allow physical network topology and traffic configurations to be anticipated. The performance of tactical mobile networks can then be enhanced by cognitive identification of the underlying characteristics of network and applying suitable networking tactics adaptively. This paper proposes a novel mathematical model-based technique utilizing cross-layer concepts in

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configuring the SDRs to give optimal performance in different tactical networking scenarios.

The paper is organized as follows: Section II lists the published work in relevant areas. Section III describes proposed design and methodology. Section IV explains simulation of several scenarios and provides extensive experimentation to investigate our approach. Sections V to VII discuss flow of proposed algorithm, testing in field to give implication of our approach and conclusion.

II. LITERATURE REVIEW

Cross-layering design techniques are an affective design strategy in dealing with challenges of intricate networks. The cooperation procedures in multi-layer vertical integration that globally optimizes radio frequency, optical spectrum, and processing resources to maximize radio coverage while meeting the QoS requirement are presented in [5] and [6]. Many researchers have opted for cross-layer designs where vital information is shared between the five TCP/IP layers to enhance the functionality of wireless networks. These functionalities may include; delay incurred by overhead generated due to headers at each layer, security, Quality of Service (QoS), and mobility [7]. Moreover, performance of wireless communication networks can be significantly improved by introducing cross-layer design in communication systems. This enables the sharing of network characteristics and application-specific requirements across multiple layers. Cross-layering can optimize delay-sensitive applications such as, video streaming by joint cooperation of multiple layers. Cross-layering presents a meaningful design for allocation of network resources for performance requirements in such applications. The quality of received video can be improved by joint coordination of the application performance parameters and transmission strategies for networking. These parameters may include placement of nodes, policies of link transmission, queuing delay and rate of video encoding. In a distributed network without a formal infrastructure, the parameters can be jointly optimized to attain the best quality of received video [8].

Another interesting cross-layer framework design is a performance-aware joint scheduling, routing, and congestion control scheme in wireless multi-hop networks. The cross-layer designs preserves the core functionalities of TCP/IP stack while allowing co-ordination, collaboration and cooperative optimization of protocols by sharing information among different layers [9].

Cross-layer routing is also suggested in vehicular ad-hoc networks. Routing remains a significant challenge in VANETs due to the dynamic characteristics of the vehicular environment. The traditional layered (OSI) model is not sufficient to make use of important parameters at the lower three layers while making routing decision. Hence, for making optimal routing decision to gain superior network performance, cross-layer routing allows information exchange with optimization of parameters at the physical, medium access control and network layers [10], [11]. Another variation of cross-layer design keeps the layers intact at design level while network status information is shared by protocols at different layers [12]. Similarly, MAC and routing functionalities can jointly work in a cross-layer manner to provide better energy and delay optimizations while moving away from strict-layered infrastructure. This scheme can reduce end-to-end packet delay and failures of packet relay [13].

In addition, the application and MAC layers have been shown to optimize 802.11e networks [14]. The continuous increase of mobile users requires an optimal utilization of the available bandwidth that is a scarce resource in tactical network-based application, such as integrated battlefield management system. To address the issue, Cognitive Radio (CR) technology represents a novel set of solutions. Concept of software defined radio has emerged as a potential solution: a software implementation of the user node enables the dynamic adaptation to the radio environment which is continuously moving and changing vicinity, available bandwidth, and delay requirements [15]. In scenarios of battlefield, the inherent properties of military-specific environment must be considered. Software defined radios provide flexibility and programmability to integrate and synchronize sharing of variety of information such as dissemination of situation awareness, file transfer, instant messaging etc. This boosts proficiencies of military forces to improve the effectiveness of deployed time and mission-critical applications [16].

However, while cross-layer models have contributed significantly towards tactical networks design challenges, there still exists a lack of a general standardized cross-layer protocol. As seen in literature, multiple parameters must be tuned according to specific application requirements that are inherently varied from each other.

Therefore, we present in this paper, a cross-layer protocol that is adaptable and configurable according to different application requirements. Our novel protocol works at application, medium access and physical layer where critical parameters can be customized to ensure QoS. The presented technique is applicable in variety of tactical networks applications. For example, mobile and robust military workstations, SDR mounted devices, smaller tactical networks in the battlefield and disaster management systems in catastrophic situation such as earthquakes, hurricanes and floods.

III. PROPOSED DESIGN

The novel idea of mathematically modeling the problem that sets dynamic parameters of an SDR for optimal performance in mission critical ad-hoc networks is presented in this paper. The proposed mathematical framework provides optimal performance subject to a set of constraints in wireless communication systems. These constraints are imposed by the physical design of the SDR, its deployment configuration and performance requirement of the application running on the SDR.

The mathematical model solves an assignment problem for a set of competing constraints for configuring critical parameters that provides optimized performance in different application-specific network topologies and scenarios. A Cross-Layer Architecture is proposed for Application Layer, Network Layer (NET), Medium Access layer (MAC) and Physical Layer (PHY) for a Multi-Hop, Self-Healing and Self-Forming tactical network of SDRs. The configuration parameters set different aspects of these layers for optimal performance.

This provides flexibility in the operation by tuning SDRs communicating in distributed fashion according to the scenario at hand for each respective transmitter in the network. This methodology gives an edge on already available cross-layer designs presented in literature which are not based on sound mathematical model and are application-specific and work best for solution of a particular problem and hence lacks the element of standardization. Many application-specific cross-layer designs are being proposed, where each focuses on a specific problem, such as video streaming [17], secure transmission, throughput optimization [18], radio power, delay optimizations etc. This raises an important issue that the cross-layer design proposed for one problem may not cater for another as they are not based on mathematical modeling.

The framework presented here configures PHY layer and NET layer parameters according to the desired input at the application layer to provide an optimal and tunable solution that selects the best trade-off of conflicting design parameters for multiple scenarios of communication link. The selected parameters are data-rate in terms of selected modulation scheme, bandwidth, delay in terms of no of hops, SDR transmit power. Ranges of values of these parameters for a typical SDR for tactical narrow-band applications are given in Table 1 [19], [20].

To test the design values for different parameters given in Table 1 are used, whereas the network path selected for a particular scenario may be peer-to-peer or multi-hop. Modulation scheme is selected according to data-rate requirements posed by the application as given in Figure 3. The block diagram for the proposed design is given in Figure 1, showing five layers of TCP/IP suit.

TABLE 1. Ranges for SDR parameters.

Parameters	Range of Values
Data-rate	$8kbps \sim 48kbps$
Delay	$1ms \sim 6ms\ (1to3hops)$
BER	$10^{-6} \sim 10^{-1}$
Power	$5watt \sim 30watt$

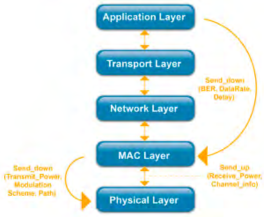


FIGURE 1. Block diagram of proposed design.

In Figure 1, the arrow going from Application Layer to MAC layer shows a function which gets the data-rate, delay and BER requirements of the application. Using this information and the channel conditions (received signal power) from the physical layer and the solution from the model, the MAC layer configures the SDR to give optimal performance. The solution facilitates the application according to desired requirements by tuning the SDR accordingly.

The proposed cross-layer design achieves the goal in two steps. The first step involves cross-layer communication of NET layer and MAC layer to generate a slot allocation vector which dynamically assigns slots to active SDRs only using CL-TDMA [21]. This is in contrast to classical TDMA which wastes time and bandwidth in scenarios of tactical ad-hoc networks where number of simultaneously communicating nodes is small as compared to commercial MANETs.

A. CHANNEL ACCESS MECHANISM

A dynamic slot allocation algorithm provides collision-free communication with low call setup time in tactical networks. The technique works by dividing the MAC TDMA frames into two phases, control phase and data transfer phase. During control phase, control messages of AODV are exchanged. At the end of this phase, we achieve three attributes:

1) Slot allocation vector for communication of active SDRs.
   During the call setup/control phase SDRs exchange control packets and based upon this control information all active radios in the vicinity gather information about communicating nodes including the received signal strength from each respective radio. The slot allocation algorithm uses information received in control packets to help all the active SDRs find slot(s) to be used for collision-free transmission of their data. As all SDRs in the topology have information about other active radios and their slots, transmission is definitely collision-free. Second phase consists of data frames for transmission of data and voice etc.
2) Routing information for all active communications. In the call setup phase, AODV control messages are exchanged to achieve adaptive slot assignment vector. During this process routing tables are generated and updated at each SDR.
3) Collecting information about receive power of active SDRs
   During the control phase AODV control messages are exchanged which are very small in size. When an SDR sends a HELLO message, it sends the message with high power and selecting modulation schemes of low data-rate to reach the far away SDRs. Each SDR that receives the HELLO message from source SDR and other relay and non-relay SDRs, it sends a reply HELLO message and adds its receive power information in reply. All SDRs record this information along with routing information.

B. METHODOLOGY

Due to the sensitive and mission-based nature of tactical networks, the communication system used is supposed to be reliable, optimized, robust and tunable because of the variable characteristics of the network environment such as catastrophic situations, battlefield, hostage situations and other mission-based scenarios.

The model explores trade-offs of important SDR configuration parameters (power, data-rate, modulation scheme, FEC selection, routing) based on constraints imposed by application and particular channel conditions and gives an optimal solution depending upon the objective function given in (1). In the model, based on the application, the algorithm assigns weights to different conflicting design parameters depending upon priorities and criticality of the application. For example, the applications like video streaming or file sharing may demand that data-rate should be high but delay is not important which means tolerable delay can be incurred. Another application may require that the delay is minimized but data-rate is lower as in transmission of aircraft tracks in airspace management systems.

The algorithm allows applications to set priorities differently in different situations. The priorities are set by scaling factors in the objective function. A set of constraints given in (2), (3) and (4) are also adjusted based on the application requirement. This feature adds flexibility to the model. The algorithm models the communication in the network as a binary Assignment Problem to be solved for guaranteed optimality using any established algorithms and tools [22], [23], [24] which is fed back to TCP/IP protocol.

This is a cognitive framework to get an optimized solution for a given scenario. The framework has been tested for different topologies with different combinations of conflicting parameters and different scenarios such as peer to peer and simultaneous communications. This section presents the designed mathematical model of the framework; objective function with various constraints posed by the applications.

The decision variable for the $0-1$ assignment problem is

$$x_{ijkm}$$

where

$$i = \text{source}$$
$$j = \text{destination}$$
$$k = \text{power options}$$
$$m = \text{modulation scheme}$$

The variable x_{ijkm} is set to 1 if source node i communicating with destination node j selects modulation scheme m and power setting k for transmission on link ij, otherwise the variable is set to 0. The designed algorithm minimizes a multi-variable objective function that selects the best trade-off based on user-defined preferences while meeting the application requirements posed as a set of constraints to the optimization model. The objective function also helps in optimizing cumulative network throughput, power, delay and BER performance. The expression for the objective function is:

$$\sum_{m=0}^{N}\sum_{k=0}^{W}\sum_{i=0}^{L}\sum_{j=0}^{L}(\alpha_{ij}\overline{\beta}_{ijkm} + \beta_{ij}\overline{d}_{ijkm} + \gamma_{ij}\overline{p}_{ijkm})x_{ijkm} \quad (1)$$

where

$$N = \text{number of supported modulation schemes in the waveform}$$
$$W = \text{number of power options of the transmitter}$$
$$L = \text{number of nodes in the tactical network}$$
$$\alpha_{ij} = \text{weight for bit error rate for the link } ij$$
$$\beta_{ij} = \text{weight for tolerable delay for the link } ij$$
$$\gamma_{ij} = \text{weight for power options f or the link } ij$$

α_{ij}, β_{ij} and γ_{ij} are different weights for setting preferences based on the deployment and application requesting communication slot on i for link ij. User has less concern for power, if SDR is vehicular mount whereas in case of man-pack deployment, power is a main concern. The application requesting communication slots also request appropriate constraints for power, delay and BER for effective communication between nodes i and j. In the objective function of (1) $\overline{p}_{ijkm}$, $\overline{d}_{ijkm}$ and $\overline{b}_{ijkm}$ are the normalized values of transmit power, delay and bit-error-rate respectively for node i for communication on link ij with modulation scheme m and power option k. The values are normalized as they have different units and are part of one objective function.

The user/application can set preferences for optimization of these parameters by assigning different weights to α, β and γ. If power is not a consideration of optimization for node i then its respective weight *gamma* is set to zero. This usually is the case for nodes that are either vehicular mounted or connected with a power source other than battery. This way objective function optimizes the concerns of communication in different tactical networking scenarios with SDR nodes in different deployment settings under a set of constraints given in section III-C.

C. CONSTRAINTS

The optimization is performed where each node specifies its requirements, these are collectively generated as a set of constraints for the optimizer. These set of constraints are given here.

1) BER CONSTRAINTS

The expression for BER constraint for node i is given in (2)

$$\sum_{m=0}^{N}\sum_{k=0}^{W} b_{ijmk}x_{ijmk} \leq B_{ij}$$
$$\text{for } \forall \text{ Nodes } i \text{ communicating link } ij \quad (2)$$

where

$$B_{ij} = \text{Threshold value of BER for link } ij$$

Depending upon the nature of communication between nodes i and j, BER constraint is set by each transmitting node i by setting a threshold value B_{ij}.

Each SDR stores receive signal strength of all the SDRs using the information of the received power in the control phase of the protocol. The value of b_{ijmk} is extracted from the performance curve as given in Figure 3 based on these stored values of SNR. The performance curves are produced by generating random bits at the transmitter. These bits are input to the Modulation Symbol Mapper (MAP), which modulates the bits into complex Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) symbols. The PSK/QAM symbols are then transmitted to the Additive White Gaussian Noise (AWGN) channel. The receiver demodulates the noisy complex symbols using a slicer and feeds the output to modulation symbol De-mapper (DEMAP). The symbol de-mapper converts the demodulated symbols to bits. The received bits are then compared with the transmitted bits to compute the BER for each SNR [25].

2) DATA RATE CONSTRAINTS

The expression for the data-rate constraint is given in (3)

$$\sum_{m=0}^{N}\sum_{k=0}^{W} r_{ijmk}x_{ijmk} \geq R_{ij} \quad \text{for } \forall \text{ Nodes } i \text{ communicating link } ij \tag{3}$$

where

$$R_{ij} = \text{Threshold value of data rate for link } ij$$

3) DELAY CONSTRAINTS

The expression for the delay constraint is given in (4)

$$\sum_{m=0}^{N}\sum_{k=0}^{W} d_{ijmk}x_{ijmk} \leq D_{ij} \quad \text{for } \forall \text{ Nodes } i \text{ communicating link } ij \tag{4}$$

where

$$D_{ij} = \text{Threshold value of delay for link } ij$$

4) ASSIGNMENT CONSTRAINTS

The expression for assignment constraint is given in (5)

$$\sum_{m=0}^{N}\sum_{k=0}^{W}\sum_{i=0}^{L}\sum_{j=0}^{L} x_{ijkm} = 1 \quad \text{for } \forall \text{ Nodes } i \text{ communicating link } ij \tag{5}$$

The constraint makes the optimizer selects only one of the possible options for node i to communicate with node j using modulation scheme m and power option k.

This proposed model is solved for a number of modulation schemes that relate to the data-rate and BER selected for communication over a certain link where the receive power translates to the distance and BER between the source and the destination SDRs for selected modulation scheme and topology. This tradeoff is shown in Figure 2 and Figure 3. A particular communication would require certain BER and a data-rate at certain range. Figure 3 translates this BER into desired SNR. To receive a signal at desired SNR at the required distance, the transmit power is to be selected based on the curves in Figure 2. More transmit power is required to achieve longer ranges for communication with a certain data-rate.

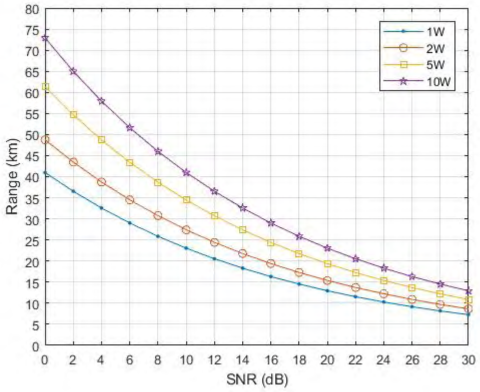


FIGURE 2. Relationship among power, SNR and distance.

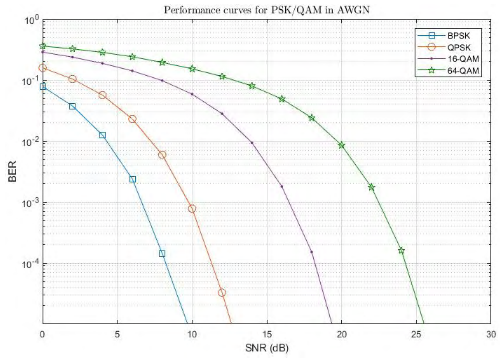


FIGURE 3. Performance curve for BER VS SNR.

IV. SIMULATION AND RESULTS

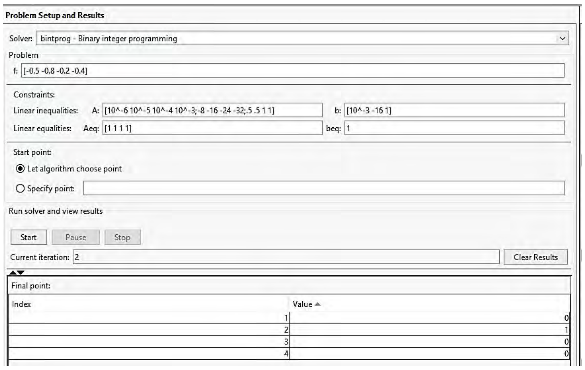
To validate our approach, different scenarios are generated with varying objective functions and constraints posed by applications and deployments. For each case an assignment problem model is generated, the model is solved using the LP solver and the results are used for setting the physical layer parameters of power and modulation scheme, and network parameter of number of hops selected for the communication. The requirements of these scenarios are tabulated in Tables 2, 3, 5, 7, 9, 11, 12 and 13. The network topologies for these communications are shown in Figure 5, 6, 7, 8, 9 and 10.

For each scenario the proposed cross-layer design, with configuration options from the solver, has been simulated and tested in OMNET++. The following example explains the methodology for a single peer-to-peer communication.

Figure 5 presents a peer-to-peer topology scenario. Here we have two radios communicating in close vicinity.

TABLE 2. **Case 1.**

Parameters	Values
Data-rate $\geq$	$16kbps$
BER $\leq$	10^{-3}
Delay $\leq$	$1ms$



Problem Setup and Results

Solver: bintprog - Binary integer programming

Problem

f: [-0.5 -0.8 -0.2 -0.4]

Constraints:

Linear inequalities: A: [10^-6 10^-5 10^-4 10^-3;-8 -16 -24 -32;.5 .5 1 1] b: [10^-3 -16 1]

Linear equalities: Aeq: [1 1 1 1] beq: 1

Start point:

● Let algorithm choose point

○ Specify point:

Run solver and view results

Current iteration: 2

Final point:

Index	Value
1	0
2	1
3	0
4	0

FIGURE 4. **OptimTool solving assignment problem of Figure 5.**

TABLE 3. **Case 2.**

Parameters	Values
Data-rate $\geq$	$8kbps$
BER $\geq$	10^{-1}
Delay $\geq$	$2ms$

Application requirements of data rate, BER and permissible delay are enlisted in Table 2.

The model generator generates the following binary assignment problem from these requirements using (1), (2), (3), (4) and (5):

Objective Function:

$$0.5x_{0000} + 0.8x_{0001} + 0.2x_{0010} + 0.4x_{0011}$$

Data Rate Constraint:

$$8x_{0000} + 16x_{0001} + 24x_{0010} + 32x_{0011} \geq 16$$

BER Constraint:

$$10^{-6}x_{0000} + 10^{-5}x_{0001} + 10^{-4}x_{0010} + 10^{-3}x_{0011} \leq 10^{-3}$$

Delay Constraint:

$$0.5x_{0000} + 0.5x_{0001} + x_{0010} + x_{0011} \leq 1$$

Assignment Constraint:

$$x_{0000} + x_{0001} + x_{0010} + x_{0011} = 1$$

The results obtained from the solver and their interpretation in terms of SDR settings are mentioned on the source node of Figure 5.

Figure 6 shows peer-to-peer topology where nodes [0] and [1] have moved farther apart still requiring $8kbps$ for communication. The model is solved and the solution is assigned to decision variable. Results are enlisted in Table 4.

Figure 7 shows peer-to-peer topology where nodes [0] and [1] have moved farther apart still requiring minimum delay of 1 hop for communication. The model is solved and the solution is enlisted in Table 6.

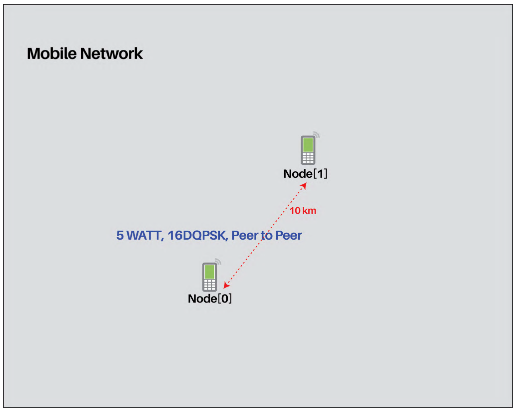


FIGURE 5. **Simulation results for scenario 1.**

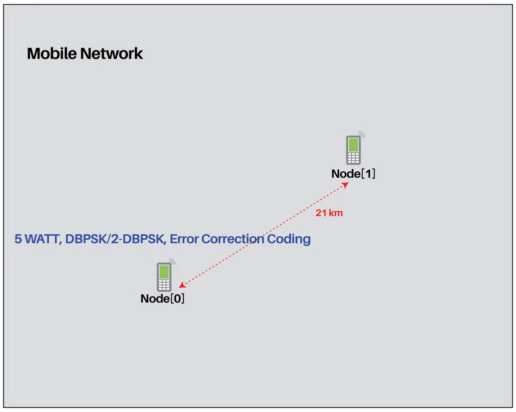


FIGURE 6. **Simulation results and topology for scenario 2.**

TABLE 4. **Results for case 2.**

Parameters	Values
Power	5 watts
Modulation Scheme	DBPSK
Error correcting coding	FEC

TABLE 5. **Case 3.**

Parameters	Values
Data-rate $\geq$	$32kbps$
BER $\leq$	10^{-4}
Delay $\leq$	$1ms$

TABLE 6. **Results for Case 3.**

Parameters	Values
Power	20 watts
Modulation Scheme	16 DPSK
Path	Peer-to-Peer

Next a topology of six nodes is considered where destination node is two hops away from source node.

5) FIRST MULTI-HOP SCENARIO

In Figure 8 node [1] wants to communicate with node [5] under the constraint of delay given in (4). The model is solved and the solution is enlisted in Table 8.

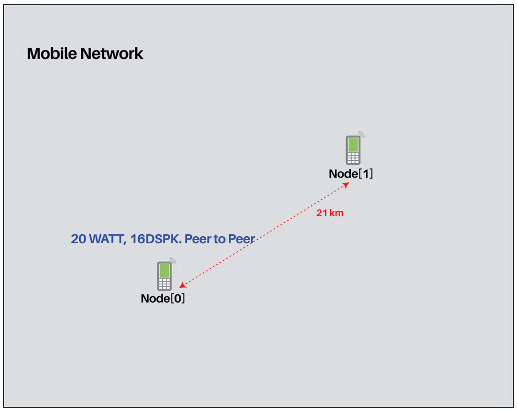


FIGURE 7. Simulation results for case 2.

TABLE 7. Case 1 for multi-hop.

Parameters	Values
Data-rate $\geq$	$16kbps$
BER $\leq$	10^{-2}
Delay $\leq$	$1ms$

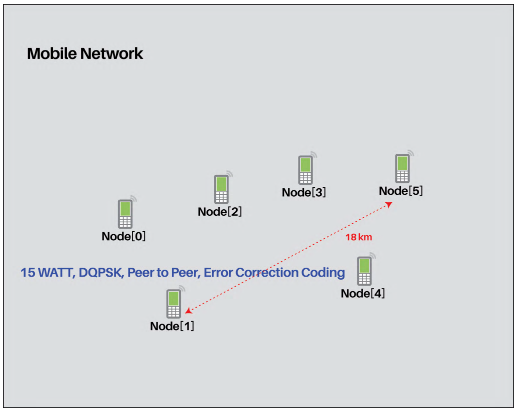


FIGURE 8. Simulation results for multi-hop case 1.

TABLE 8. Results for Multi-hop case 1.

Parameters	Values
Power	15 watts
Modulation Scheme	DQPSK
Error Correction Coding	FEC

TABLE 9. Case 2 for multi-hop.

Parameters	Values
Data-rate $\geq$	$32kbps$
BER $\leq$	10^{-4}
Delay $\leq$	$3ms$

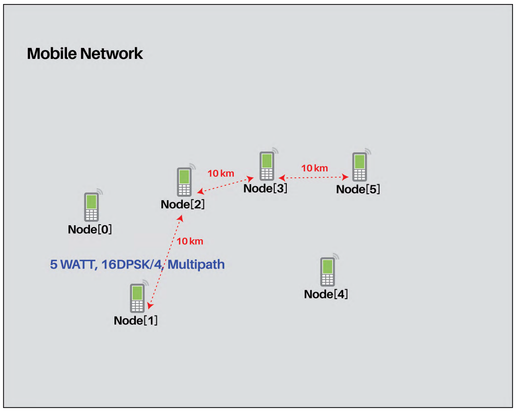


FIGURE 9. Simulation results for multi-hop case 2.

TABLE 10. Results for multi-hop case 2.

Parameters	Values
Power	5 watts
Modulation Scheme	DQPSK
Path	Multi-hop

TABLE 11. Parameters for first communication.

Parameters	Values
Data-rate $\geq$	$8kbps$
BER $\leq$	10^{-1}
Delay $\leq$	$1ms$

TABLE 12. Parameters for second communication.

Parameters	Values
Data-rate $\geq$	$32kbps$
BER $\leq$	10^{-4}
Delay $\leq$	$1ms$

TABLE 13. Parameters for third communication.

Parameters	Values
Data-rate $\geq$	$32kbps$
BER $\leq$	10^{-4}
Delay $\leq$	$3ms$

TABLE 14. Results for first communication.

Parameters	Values
Power	5 watts
Modulation Scheme	16DPSK
Path	Peer-to-Peer

6) SECOND MULTI-HOP SCENARIO

In Figure 9 node [1] wants to communicate with node [5] under the constraint of BER of 10^{-4}. The model is solved and the solution is enlisted in Table 10.

7) USE CASE SCENARIO FOR SIMULTANEOUS COMMUNICATIONS

This case illustrates a complex situation where we have three simultaneous communications. In Figure 10, source node [0] labeled as s1 wants to communicate with destination node [1] labeled as d2, source node [5] labeled as s2 wants to communicate with destination d2 with node id [3] and source node [8] labeled s3 wants to exchange information with destination node [4], d3. All three communications have different configuration requirements and constraints. Table 11, 12 and 13 enlist parameters for communications. The model is solved and the recommended solutions are enlisted in Table 14, 15 and 16.

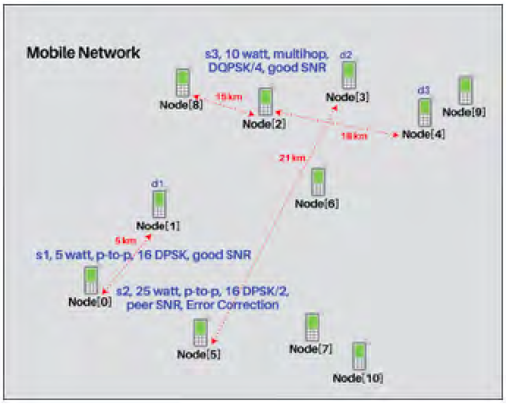


FIGURE 10. Simulation results for simultaneous communications.

TABLE 15. Results for second communication.

Parameters	Values
Power	25 watts
Modulation Scheme	16DPSK/2
Path	Peer-to-Peer

TABLE 16. Results for third communication.

Parameters	Values
Power	10 watts
Modulation Scheme	DQPSK/4
Path	Multi-hop

V. ANALYSIS OF RESULTS

The flexible nature of proposed cross-layer framework enables SDRs to be dynamically tunable to yield optimal performance for a defined objective function under a set of performance constraints for communication in tactical networks. For example, if the user has selected delay parameter to some tolerable extent and power to be preserved, the model generates a solution where the SDR tunes itself to low power and multi-hop mode even though the high power and peer-to-peer option is also feasible. This solution makes sense as it saves the SDR power which is a scarce resource in mission critical networks, hence providing the optimized solution based on application demands. On the other hand, if constraints are set for some critical and time-sensitive data to be transmitted and delay is intolerable, the model generates a solution that tunes the SDR to high power and peer-to-peer mode to cater for the criticality of the communication scenario. The data-rate and BER are also constraint-dependent. For example, if constraints are set for the SDRs that are distant then the solution will opt for an appropriate error-correction scheme to reduce BER and improve SNR. At one time, different SDRs may have different objectives and constraints, the algorithm provides optimal solution for each link for the transmitting radios to be set according to the solution of the model.

Several experiments are performed as listed in Section IV. The requirements are coming from the application, so we set different parameters and constraints in the model, the model is solved and it gives us the best trade-offs which are then used to configure the radio for optimal network operation. For example in scenario 1, given in Figure 5, two SDRs want to communicate. We found out that the model provided us with an optimized configuration. These output configuration parameters of PHY layer are calculated according to the requirement of application by the model. They are displayed on source node in Figure 5. Here, basic constraint posed by application is that BER should be less than or equal to 10^{-3} and delay should be minimum, not greater than 1ms. Model calculates the transmission power to be 5 watt and accordingly an appropriate modulation scheme is selected which in this particular case is 16DPSK. Model resolves the problem by taking two main parameters in consideration:

- As nodes are not far apart, and allowed data rate is up-to 16kbps, sending data at this rate fulfills the delay constraint because of the close vicinity.
- Secondly BER is supposed to be less than 10^{-3}, so model computes a solution that suggests tuning the SDRs at higher data-rate and low power which will not affect the delay or BER constraint because nodes exist in close vicinity. This will preserve the power of SDRs for more critical scenarios.

In the second scenario, shown in Figure 6, peer-to-peer topology nodes have moved further apart and more power will be required to enable communication between these nodes. Model calculates output configuration parameter of PHY layer according to the requirement of applications. They are displayed node in Table 4. Here basic constraint posed by application is that data rate should be strictly less than or equal to 8kbps and delay is tolerable to 2ms/2hops. In this case where mobile SDRs have moved far apart, PHY layer can have two different configurations depending upon the requirements of the application.

- In the scenario depicted in Figure 6, Model generates a solution that tunes SDRs at low power, and lower data rate with error correction coding to cater for poor SNR. This configuration enhances the chances of error and data corruption because of the channel impairments. Delay will also increase, this type of configuration may work best in scenarios where less critical data is to be transmitted.
- For other set of application requirements given in Table 5, model finds a solution that tunes the SDRs at high power, high data rate with good SNR. Evidently this configuration will increase the cost of communication in terms of power consumption, but on the other hand data integrity and BER will improve. Delay will also be minimized. This configuration will work efficiently for transmission of critical information among SDRs. This scenario is illustrated in Figure 7.

Tuning radio to high power will improve SNR and reduce delay which are critical demands of scenarios such as catastrophic situations where identifying the location of the event is critical and requires quick response/action with reasonable accuracy. The above two scenarios give a clear trade-off between critical parameters to handle situations of different nature demanded by the application.

Next we discuss a multi-hop scenario, where six nodes are taken for conducting the simulation, shown in Figure 8. Application requirements are enlisted in Table 7. The model is solved and the solution resolves this scenario where SDR has ample power and delay is to be minimized. Again this configuration will work best for highly time-critical applications. Availability of high power allows SDRs to communicate in peer-to-peer fashion with minimum delay and good SNR. This configuration will choose path as peer-to-peer rather than going for multi-hop. Selected configuration is enlisted in Table 8. Delay constraint cannot be satisfied if chosen path is multi-hop. However, peer-to-peer path will increase power consumption of SDRs.

Now if application requirements change, model will solve the problem to give a different setting. Table 9 shows new requirements posed by application. In this scenario the model calculates configuration parameters of SDRs for multi-hop and low power setting as delay and data rate are not critical, hence the model provides optimized configuration for communicating SDRs, where SDR power is preserved. New settings are displayed in Table 10. For example, some applications may want to share less critical information such as periodic updates from the catastrophic area. Time is not very important in this case as updates are sent after a set period of time and permissible data rate is sufficient for multi-hop relaying to preserve power of SDRs for more critical scenarios. Multi-hop communication among SDRs incur delay so it will work best for the situation under discussion where delay is not critical to complete the task. Such a configuration may optimize the transmission of information in applications such as communication in hostile areas.

Next, we discuss a scenario where multiple communications are being conducted simultaneously. All these communications have different configuration requirements and constraints. The model solves the problem and provides optimized PHY layer parameters according to the demands of each communication posed by different applications running on SDRs. The model resolves each problem in optimized fashion such that solution ensures that simultaneous communications do not compromise the optimization of resources available.This scenario is illustrated in Figure 10.

VI. TESTING IN FIELD

The proposed methodology is implemented on SDRs for deployment in a tactical network settings of Artillery Command & Control System. The deployment and command hierarchy of the system is shown in Fig.11. This deployment is performed in 20x20 sq. km. The main components of the system are enlisted in Table 17 along with their roles.
Field Testing conditions are given in Table 18.

Types of data used for field testing is enlisted in Table 19.

Adjutant and OP are 20 sq. km apart. As mentioned in Table 17 OPs mark target and send area observation parameters such as co-ordinates of an object of interest to CP.

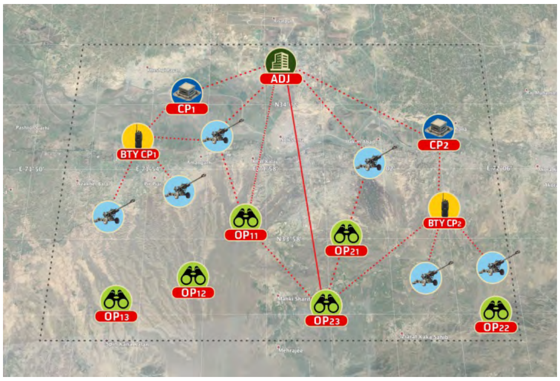


FIGURE 11. Tactical network for artillery command & control system.

TABLE 17. Components of artillery command & control system.

No.	Component	Role
01	Observation Post (OP)	OP marks target and sends their co-ordinates to Command Post (CP). OP also receives fire plans and maps from Adjutant (ADJ) and CP.
02	Command Post (CP)	CP analyzes data received from OP and performs calculations for selection of appropriate guns.
03	Battery Command Post (BTY CP)	BTY CP sends firing instructions to the selected gun nodes.
04	Adjutant	Coordinates with higher echelons

TABLE 18. Field testing conditions.

Vicinity	
Area range	20 sq. km
Terrain	Nowshera, Pakistan
No of Node	13

TABLE 19. Data types.

No	Type of Data	Example Data
01	Non-real time	Communication of maps, fire plans etc.
02	Real time	Communication of commands such as fire for effect.

They also have information about plans and maps, which they receive from ADJ and CP. Let us first discuss the scenario where system communicates non-real time data among different nodes. This type of data communication is not critically delay sensitive because of the non-real time nature of the information being shared. For this type of data transfer, the model is solved and the solution selects configuration that keeps transmission power low, data rate high in a multi-hop topology. In Figure 11, transfer of non-real time data such as maps and fire plans is performed between ADJ and OP23 where CP2 and BTY CP2 are used as relay nodes. Configuration of networking parameters is given in Table 20.

Next we discuss transmission of real-time critical data such as commands for fire. This type of data communication is delay sensitive, situation critical and requires prompt response.

TABLE 20. **Configuration parameters.**

No	Parameters	Values
01	Transmission Power	1 watt per hop
02	Topology	Multi-hop
03	Data rate	$24kbps$
04	Delay	Near real time

TABLE 21. **Configuration parameters.**

No	Parameters	Values
01	Transmission Power	10 watt per hop
02	Topology	Peer-to-peer
03	Data rate	$8kbps$
04	Delay	Real time

- Response 01
  CP1 directly sends command to appropriate gun according to the information received from ADJ, as can been seen in Figure 11. The model is solved and the solution provides configuration as shown in Table 21.
- Response 02
  CP1 sends command to BTY CP1 which then selects an appropriate artillery gun according to the information received.
- Response 03
  After fire, all nearby OPs collect co-ordinates of the fire and transfer it to nearby CPs. CP observes the co-ordinates, analyzes the success or failure of the fire, deviation from target and re-calculates the new co-ordinates for next command.

VII. CONCLUSION

The novel model of a cross-layer design presented in this paper provides a flexible and configurable solution for time and mission critical applications in a network setting. It provides an edge over other cross-layer designs presented in literature in the aspect of non-uniformity and co-existence, where each design solves one particular problem such as saving power, optimizing bandwidth, reducing delay or achieving optimal data rate and good SNR. This design is a major step towards providing a standard cross-layer design based on sound methematical model for optimizing multiple competing parameters such as power vs delay, delay vs topology, data rate vs power etc. This is achieved by exploiting the dynamic and run-time configurability of the SDR by setting its physical layer parameters for the options given by the solver of the mathematical model. The framework has been validated with simulation results generated by OMNET++ and trial of the SDRs in the field.

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